USACERL Technical Report M-91/06
January 1991
Rapidly Erectable Lightweight Mobilization Structures

US Army Corps
of Engineers
Construction Engineering
Research Laboratory

AD-A231 699

Evaluation of K-Span as a Rapidly Erectable Lightweight Mobilization Structure (RELMS)

by
Steven Sweeney
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To meet the increased need for facilities during a possible mobilization, the Army is evaluating new construction technologies for potential use as Rapidly Erectable Lightweight Mobilization Structures (RELMS). The K-Span building system has been studied as one such technology. K-Span has many characteristics that would be beneficial for mobilization construction. Field tests have shown that it is erected easily and quickly. Most skills involved are simple and repetitive. With the majority of the structural components fabricated onsite, the system is both low-volume and lightweight. The specialized roll-forming machine and accessories are trailer-mounted and transportable. Costs are very competitive with conventional construction techniques. Structural integrity of the system is sound, such that medium-to-large-span structures could be constructed in moderate to severe snow and wind load conditions. Load capacities are even higher for short structures on which end wall effects can be considered.

Disadvantages of the system include the need for specialized equipment for construction. Besides the forming machine, a crane or high mast forklift is required to lift the arches into place. It is best to have a manlift or cherry picker for end wall construction, and a welder and cutting torch are required. Earth working equipment may also be required, depending on site conditions and foundation design.

Based on availability, K-Span could provide a small portion of early mobilization requirements. With 28 machines currently available to produce the systems, a maximum of 420,000 sq ft/day of bare structure could conceivably be completed with short lead time. To take full advantage of the rapid erectability of the system, enough steel would have to be stockpiled for about 2 weeks' construction. After that time, the steel industry's ability to produce galvanized sheet steel would far exceed the capacity of the available K-Span equipment.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
January 1991

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Evaluation of K-Span as a Rapidly Erectable Lightweight Mobilization Structure (RELMS)

5. FUNDING NUMBERS
PE 4A162731
PR AT41
TA E
WU 079

6. AUTHOR(S)
Steven Sweeney, Demetres Briassoulis, and Anthony Kao

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory (USACERL)
2902 Newmark Drive, PO Box 4005
Champaign, IL 61824-4005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR M-91/06

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Chief of Engineers
ATTN: DAEN-ZCM
Pentagon
Washington, DC 20310

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

To meet the increased need for facilities during a possible mobilization, the Army is evaluating new construction technologies for potential use as Rapidly Erectable Lightweight Mobilization Structures (RELMS). The K-Span building system has been studied as one such technology. K-Span has many characteristics that would be beneficial for mobilization construction.

Based on availability, K-Span could provide a small portion of early mobilization requirements. With 28 machines currently available to produce the systems, a maximum of 420,000 sq ft/day of bare structure could conceivably be completed with short lead time. To take full advantage of the rapid erectability of the system, enough steel would have to be stockpiled for about 2 weeks' construction. After that time, the steel industry's ability to produce galvanized sheet steel would far exceed the capacity of the available K-Span equipment.

14. SUBJECT TERMS
Rapidly Erectable Lightweight Mobilization Structures (RELMS)
mobilization K-Span construction

15. NUMBER OF PAGES
66

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

FOREWORD

This research was performed for the Office of the Chief of Engineers (OCE) under Project 4A162731AT41, "Military Facilities Engineering Technology"; Task Area E, "Military Engineering"; Work Unit 079, "Rapidly Erectable Lightweight Mobilization Structures." The OCE technical monitor was Michael Shama (DAEN-ZCM).

The research was conducted by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. Demetres Briassoulis is a visiting assistant professor at the University of Illinois, Urbana. Also providing assistance with this project were James Wilcoski and Randel Groh of USACERL.

Dr. Paul Howdyshell is Acting Chief of EM. COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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EVALUATION OF K-SPAN AS A RAPIDLY ERECTABLE LIGHTWEIGHT MOBILIZATION STRUCTURE (RELMS)

1 INTRODUCTION

Background

Studies by military planners indicate that in the event of full mobilization a serious shortage of supporting structures and facilities would exist. Estimates show that peak populations, and therefore peak facility shortages, would occur as early as day M + 28.[1] Alternatives by which this shortage could be overcome include using commercially available properties, doubling occupancy of facilities, erecting temporary structures, and constructing new facilities. The important criteria for each option are immediate occupancy and cost-effectiveness. The situation will differ at each installation; however, some combination of these alternatives (as well others) will be used.

Among the alternatives, new construction is probably the least desirable in terms of time and cost, but would be unavoidable if all demands were to be met. For this reason, the Army is evaluating building systems for potential use as Rapidly Erectable Lightweight Mobilization Structures (RELMS). The K-Span building system has been identified as potentially well suited to RELMS applications. The structural shell is fabricated completely onsite from coil sheet stock material.[2] The manufacturer has demonstrated that a 12-person crew can construct 5000 sq ft[*] of bare structure (no utilities) in 12 hr.

At the time of this study, K-Span roll forming system was manufactured and sold by G.A. Knudson, Ltd. Since then, rights to the system have been obtained by MIC Industries.

The U.S. Army Construction Engineering Research Laboratory (USACERL) was asked to evaluate the feasibility of using K-Span in mobilization construction. Preliminary work involving a numerical analysis of the structure has been reported elsewhere.[3]

Objective

The objective of this study was to evaluate K-Span system performance in all aspects of mobilization construction and determine if this system could be used in a full-scale mobilization.

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[1] U.S. Army Engineer Studies Center, *Corps Mobilization Capabilities, Requirements, and Planning* (U.S. Army Corps of Engineers, March 1980).

[2] *K-Span, Metal Building Data Manual* (G. A. Knudson [USACE], Ltd., Washington, DC).

[*] Metric conversion factors are given on page 51.

[3] D. Briassoulis, et al., *Determination of Ultimate Loads for Corrugated Steel Barrel-Type Shell Structures* Technical Report M 88/01/ADA187716 (U.S. Army Construction Engineering Research Laboratory [USACERL], October 1987).

Approach

Information on cost, availability, building design, and constructibility was collected from the manufacturer and independent contractors. Material suppliers and contractors were surveyed to determine the overall availability of the structures. Laboratory testing was conducted to determine the structural integrity of the system. Material testing was performed to determine the structure's resistance to corrosion. Construction projects that used K-Span were monitored to further evaluate constructibility of the system.

Scope

This final report on the potential use of K-Span in mobilization construction is a comprehensive summary of all findings. It includes results of the laboratory tests on beam sections and full arch section of the structure. Results of the numerical analysis performed on the structure were reported in USACERL Technical Report M-88/01.

Mode of Technology Transfer

Results of this study are to be transferred to U.S. Army Corps of Engineers District offices and to Army installations through the FY 91 Technology Transfer Test Bed (T^3B) program. Information in this report can be incorporated into future mobilization plans that include K-Span structures. In addition, new construction planners (for nonmobilization missions), can use these findings in determining the feasibility of K-Span as an alternative to conventional structures.

2 BUILDING SYSTEM DESCRIPTION

General

The K-Span building is a thin-gauge metal barrel-vault structure that is fabricated onsite from coil sheet stock materials.

The sheet steel is fed continuously into the K-Span roll-forming machine, which cold works the material into a straight channel section and cuts it to the desired length. The channel is then fed into the second stage of the forming machine which curves it to the desired radius.

There are actually three K-Span systems: the K-Span, the Super-Span, and the Econo-Span. Each system uses a different width sheet steel and/or produces a different width and cross sectioned panel. The major focus of this study is on the K-Span system; however, in most cases, the information is relevant to all three.

Some details of the Super-Span were obtained while evaluating a construction project at Fort Drum, NY. In all systems, structures can vary in width and height, and can be built to any length. The K-Span design manual[4] provided by the original equipment manufacturer includes structures from 30 ft by 12 ft (width by height) to 72 ft by 26 ft. Arch sections are formed to the structure's height and width and seamed together to obtain the desired building length.

Structural Shell

Each 1-ft K-Span arch section is a continuous channel section cold-formed from 24-in.-wide coil stock (Figure 1a). The channels are then curved to the radius of the structure, forming the arch panels with minor corrugations (Figure 1b). Arch panels are seamed together by crimping one top flange around another to form the corrugated barrel vault shell (Figure 2). Straight channel sections are used to form the vertical end walls.

Foundation

Standard practice is a cast-in-place pile and bond beam construction. Arch ends are encased in the band beam to provide a fixed condition.

Materials

The most common material used is galvanized sheet steel conforming to American Society for Testing and Materials (ASTM) Standards A 446-72 and A 525-73, grade C (40,000 psi minimum yield point) or grade D (50,000 psi minimum yield point), coating class G-90.[5] Thicknesses used can vary from 0.023 in. (24 gauge) to 0.040 in. (19 gauge). Other materials may be possible but are not commonly used and therefore were not considered in the numerical analysis and load testing. Aluminum samples were used in the material exposure test.

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[4] *K-Span, Metal Building Data Manual.*

[5] American Society for Testing and Materials (ASTM), *Annual Book of Standards* (1987).

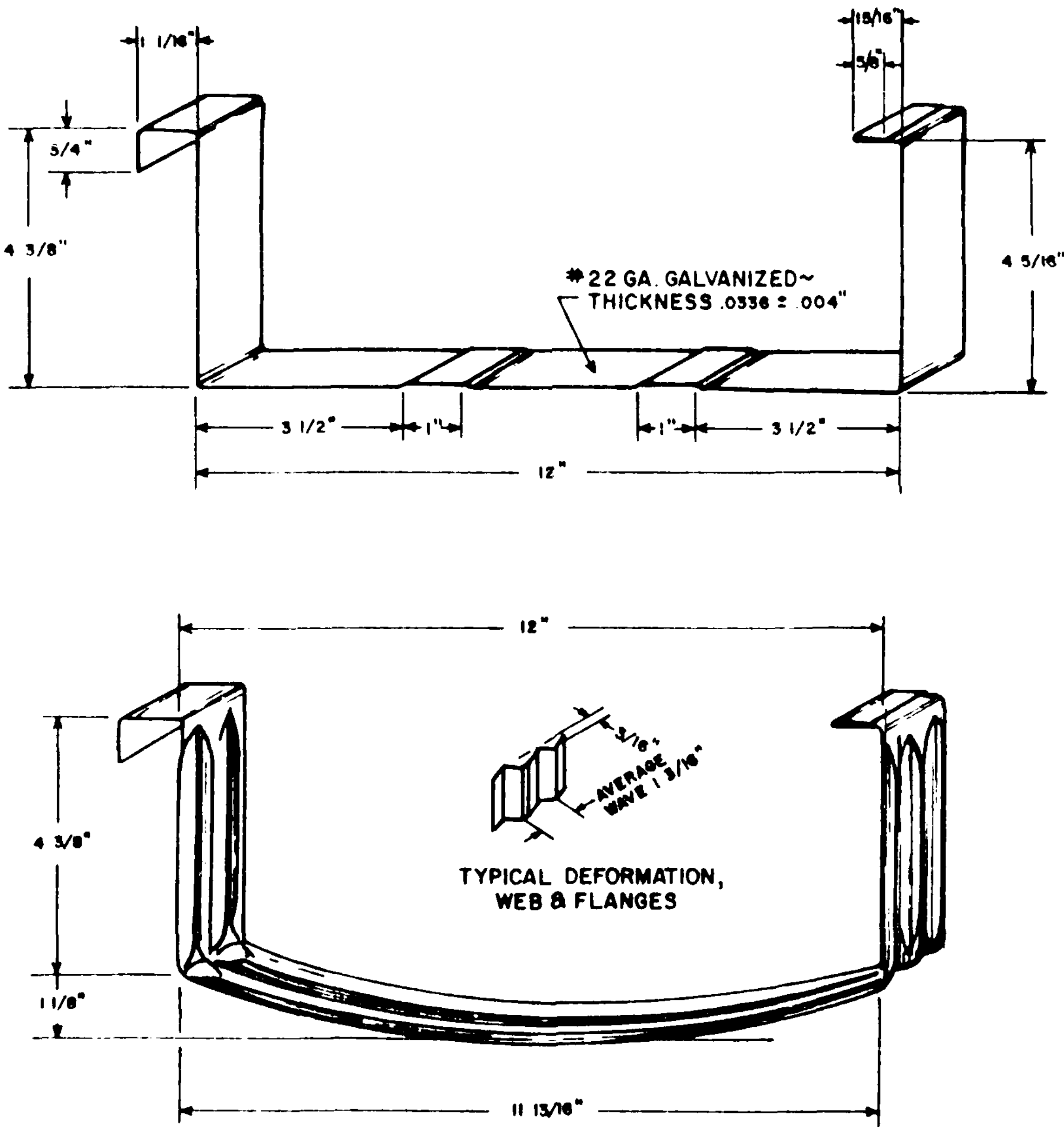


Figure 1. Roll-formed cross sections of the (a) straight and (b) curved K-Span panels.

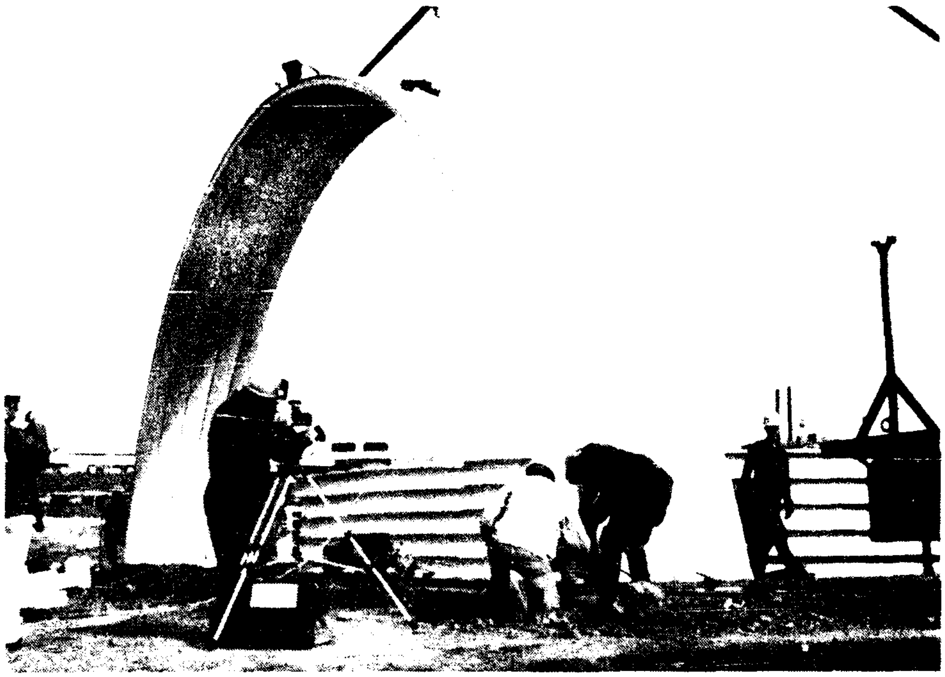


Figure 2. Shell formed by seaming multiple curved panels together.

3 PHYSICAL CONSIDERATIONS

Constructibility

Constructibility is determined by the type of equipment, the level of construction skills, and the number of physical hours and manhours required to complete the structure. K-Span has been evaluated at two construction projects on military installations. One 50 by 18 by 110 ft (width by height by length) K-Span structure was constructed at Fort Carson, CO; three 55 by 20 by 100 ft and one 55 by 20 by 80 ft Super-Span structures were constructed at Fort Drum, NY. Information was obtained through direct observation of activities, interviews with the K-Span contractor, and feedback from Government personnel involved with the projects.

Equipment

The recommended equipment and tools for constructing the basic K-Span shell are listed in Table 1. These items are grouped as equipment which is part of the K-Span system, heavy equipment, tools, and concrete placement equipment. Additional equipment requirements will vary, depending on site conditions and electrical, plumbing, and mechanical systems included in the project.

Manpower

Manpower requirements are based on data obtained from the military construction projects described above. At Fort Carson, the K-Span contractor and a factory representative supervised and demonstrated the construction procedures, with most of the work performed by military personnel. The Fort Drum project also used inexperienced military personnel supervised by the contractor and two assistants.

Special skills required for construction are determined by the equipment used. An engineer is required to level and lay out the site. Trained operators are necessary for all heavy equipment. A crane operator and manlift operator are needed, as well as a welder. At least one person should be experienced in concrete finishing. Specific skills in mechanical, electrical, and plumbing systems may also be needed; however, for this evaluation, only the basic shell structure was considered.

The construction data summarized in Table 2 show that the K-Span system took 0.078 manhours/sq ft and Super-Span took 0.113 manhours/sq ft to construct the basic shell. Additional time was required for the foundation and forms of the Fort Drum Super-Span structures because the deeper profile required larger forms and more concrete. Super-Span end wall details are more complicated than those of K-Span and also took extra time. The difference in panel width of the two systems does not significantly change construction times. Super-Span arches are twice the width of K-Span panels. Although fewer arches are needed, they are more difficult to handle and require additional manpower per arch. All other activities were comparable between the two systems.

Time

The projects showed that the number of hours required for each task depends on crew size. The onsite training of workers and limited number of crew members increased the total time to complete the projects over that expected under more optimal conditions. The key limiting factor in maximum production of K-Span structures was the output of the machine. With enough personnel, a single machine can roll enough steel to produce 5000 sq ft of structure in 8 hr. This includes time to set up the equipment and any minor

Table 1

Recommended Equipment for K-Span Construction

K-Span System Equipment:

- Roll-Forming Machine
- Seamer
- Concrete Forms
- Spreader/Lift Bar
- Vise Grip C-Clamp

Heavy Equipment:

- Earth Working Equipment (to Level Site)
- Post Hole Digger, 1 ft Diameter, 6 ft Deep
- Manlift or Cherry Picker
- Portable Welder w/ Generator
- Oxygen/Acetylene Cutting Torch
- Crane (5-Ton Capacity)
- Generator or Power Source for Power Tools

Tools:

- Rebar Cutter
- Drill-Powered Screwdriver
- Heavy-Duty Cut-Off Saw (Chop Saw)
- 100-Ft Tape Measure
- 25-Ft Tape Measure
- Vice Grip
- 100-Ft Extension Cord
- Transit
- 4-Ft Level
- Caulking Gun
- Shovel
- Framing Square
- Ladder (20 Ft Adjustable)
- Pry Bar (Large)
- Carpenter's Hammer (1 Lb)
- 3-lb Hammer
- 10-lb Hammer
- 3/8 In. Socket Set
- 1/2 In. Socket Set
- 3/8 In. to 1-1/4 In. Combination Wrench Set
- Screwdriver Set

Concrete Placement Equipment:

- Vibrator
- Trowel
- Edger
- Cement Buggy

Table 2

Time and Manhour Requirements for Construction*

Activity	Hours	Manhours
Fort Carson (5500 sq ft; 1 K-Span Structure):		
Foundation	20	90
Setup	1	16
Roll Form Sections	14	77
Erect Arches	17	56
Place Concrete Forms	14	72
Construct End Walls	22	85
Place Concrete	4	34
Total Manhr = 430 (0.078 manhr/sq ft)		
Fort Drum (20,900 sq ft; 4 Super-Span Structures):		
Foundation	48	456
Setup	8	80
Roll Form Sections	46	266
Erect Arches	32	170
Place Concrete Forms	80	384
Construct End Walls	100	725
Place Concrete	24	288
Total Manhr = 2369 (0.113 manhr/sq ft)		

*Hours and manhours were recorded directly, approximated based on production rates recorded directly, or based on information provided by the contractor, military personnel, and civilian Government employees participating in the project.

downtime. An estimate of optimal crew sizes per construction activity to maximize use of the forming machine is shown in Table 3.

Total time for completing a structure depends on the manpower available. The basic 5000-sq ft structure (no utilities or site preparation) can be completed by experienced crews (as listed in Table 3) in 40 working hours. Depending on foundation design, there may be some delay to allow for the concrete to set. Foundations of ground anchors or a cast-in-ground bond beam (no caissons) are feasible alternatives in a mobilization situation.

Availability

The availability of K-Span depends on two key factors--equipment and material. Each of these items was evaluated to determine lead time and limitations for K-Span in mobilization construction. Coating (painting) the steel prior to construction was not considered essential for mobilization construction; therefore, this additional lead time was not considered.

Equipment

A list of K-Span contractors was provided to the Government by a representative of G. A. Knudson, Ltd. This list was based on sales of K-Span equipment and knowledge of equipment resales. The contractors were contacted to determine their construction capabilities and material stock. If the equipment had been sold, the purchaser was contacted when possible.

Table 4 lists the machine owners located in the survey. It also includes three machines purchased by U.S. Army Forces Command (FORSCOM) in 1988 for mobilization studies. Twenty-eight machines are located across the United States, as shown in Figure 3. The survey was completed in 1988, therefore some changes are expected. The two machines listed as inventory at G.A. Kundson, LTD, for example, have most likely been sold or transferred to MIC Industries.

Material

The basic material is the coiled sheet steel. For the 5000-sq ft structure, about 23,000 lb of sheet steel coil is required. Total volume of the steel is about 500 cu ft. In addition, 600 lin ft of 3-in. steel angle and 2000 lin ft of No. 4 reinforcing bar are needed, together weighing 5600 lb. The caissons and bond beam foundation require 30 cu yd of concrete. Materials for door frames, doors, ventilation, and mechanical, electrical, and water distribution systems are not included in the basic building system and must be added.

To determine material availability, as many major steel manufacturers and suppliers as possible were contacted. The questions asked were: (1) what is your current stock of material and (2) if the highest possible production of galvanized sheet steel were requested, what would be the expected lead times and production rates? Responses to the survey are summarized in Table 5. Total availability is shown graphically in Figure 4.

Analysis of Availability

Assuming 24 hr/day operation at maximum production, a single K-Span machine can roll-form steel for three 5000-sq ft structures, totaling 35 tons of steel per machine per day. With 28 machines,

Table 3

Crew Sizes Needed To Maximize Forming Machine Efficiency

Responsibilities	Crew
Layout and Foundation	10
Setup, Form, and Erect Arches	10
End Wall Construction	9
Form Work and Place Concrete	12
Hang Doors	3

Table 4

Owners of K-Span Equipment (1988)

Owner	Location	Number of Machines
Cyclone Shops, Inc.	Huntingburg, IN	3
Hurricane Construction	Jasper, IN	1
Huntington County Coop Lumber	Huntington, IN	1
Ken's Company	Dwight, IL	1
Seam Fast Builders	Webster City, IA	1
Mr. Tommy Wayne Gift	Louisville, KY	1
Rainbow Steel Buildings, Inc.	Addis, LA	1
Mr. Joe Fontenot	Mamou, LA	2
American Systems, Inc.	New Brighton, MN	1
Internat'l Steel Erectors, Inc.	Anchorage, AK	1
K-Span Colorado, Inc.	Colorado Springs, CO	1
Budget Sales, Inc.	Idaho Falls, ID	1
Enterprise Sales Company	Valley City, ND	1
Jacobson Steel, Inc.	Moreland, ID	1
Heaney Construction	American Falls, ID	1
Mr. Dave Shelver	Devils Lake, ND	1
Mr. Jack Gilbert	Olive Branch, MS	1
Seven Day Builders	St. Louis, MO	1
Stonyridge Realty	New Carlisle, OH	1
Stewart and Associates	Vienna, WV	1
G. A. Knudson, Ltd.	Broomfield, CO	2
U.S. Army Forces Command	Fort Drum, NY	1
U.S. Army Forces Command	Fort Lewis, WA	1
U.S. Army Forces Command	Fort Stewart, GA	1
		TOTAL = 28

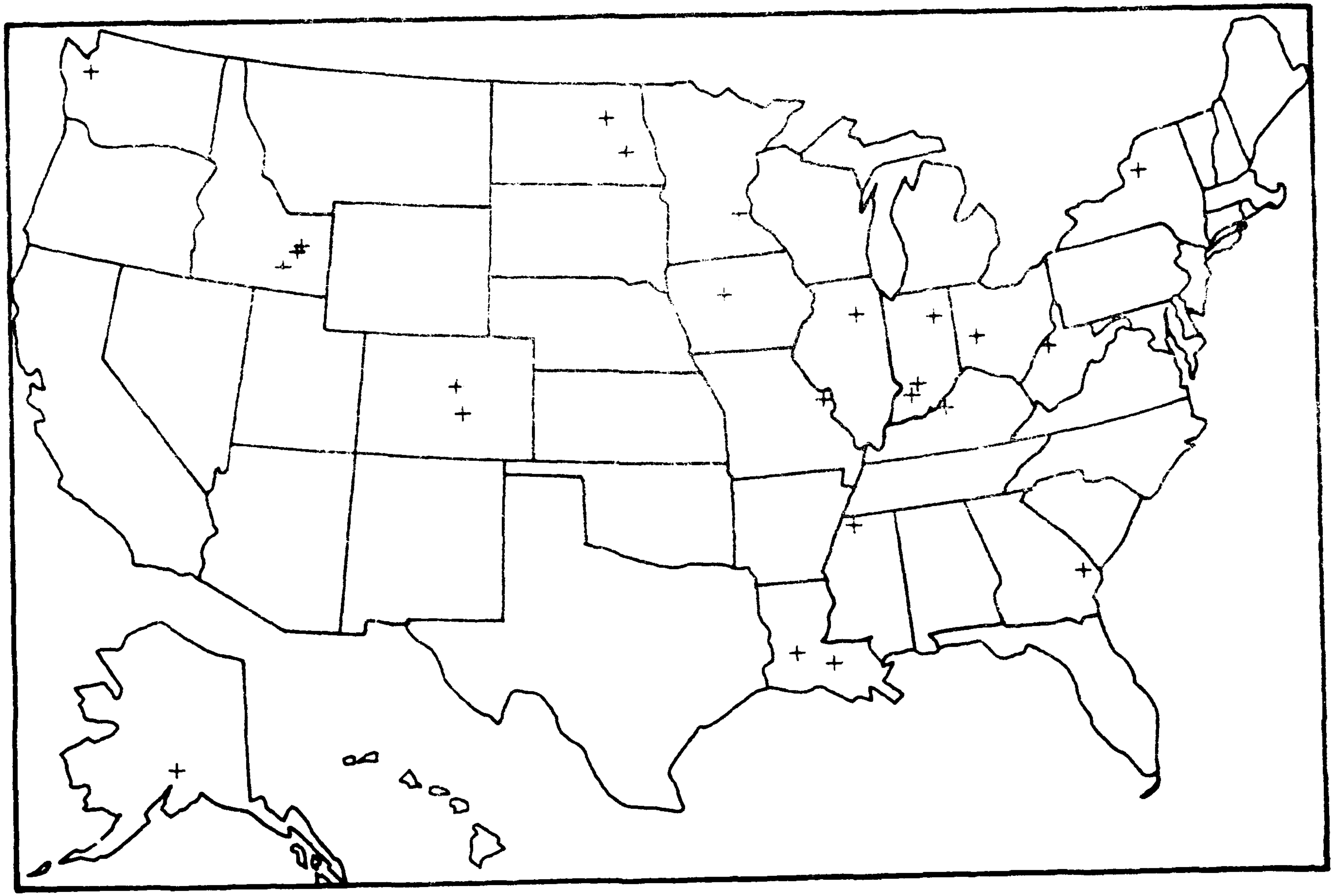


Figure 3. Locations of K-Span equipment in the United States (1988).

Table 5

Material Availability From Sheet Steel Suppliers and Producers

SPECIFICATIONS: ASTM A446-72 AND A525-73, GRADE C (40KSI) OR D (50KSI)
COATING CLASS G-90, GALVALUME OR ELECTROLITIC GALVANIZED IF A446-72 IS MET
24 IN. WIDE, 5,000 LB. COILS
THICKNESS OF .023, .029, .035, AND .040 IN.

COMPANY*	LOCATION	STOCK	TOTAL CAPACITY	PRODUCTION EACH WEEK AFTER DATE OF ORDER (TONS) 0	1	2	3	4	5	6	7	8	9
SUPPLIERS:													
ARMCO INC. EASTERN STEEL DIV.	BALTIMORE, MD	1000	8500	1000	544	544	2550	2550	2550	6800	6800	8500	8500
ARMCO INC. EASTERN STEEL DIV.	BALTIMORE, MD		2200	0	141	141	660	660	660	1760	1760	2200	2200
g ARMCO INC. EASTERN STEEL DIV.	BURNS HARBOR, ID.		5000	0	320	320	1500	1500	1500	4000	4000	5000	5000
e ARMCO INC. EASTERN STEEL DIV.	WALBRIDGE, OH		1150	0	74	74	345	345	345	920	920	1150	1150
e BETHLEHEM STEEL CORP.	BUFFALO, NY		3850	0	246	246	1155	1155	1155	3080	3080	3850	3850
BETHLEHEM STEEL CORP.	FONTANA CA.		300	0	0	0	0	300	300	300	300	300	300
BETHLEHEM STEEL CORP.	PERRY, OH.		1000	0	0	0	0	0	0	1000	1000	1000	1000
BETHLEHEM STEEL CORP.	RIVERSIDE, IL.	400	0	400	0	0	0	0	0	0	0	0	0
BETHLEHEM STEEL CORP.	WARREN, OH.		3350	0	0	0	0	402	3350	3350	3350	3350	3350
CALIFORNIA STEEL INDUSTRIES	HENNEPIN, IL.		7500	0	0	0	0	900	7500	7500	7500	7500	7500
EMPIRE DETROIT STEEL DIV.	INDIANA HARBOR, IN.		9300	0	0	0	0	1116	9300	9300	9300	9300	9300
e FAIRMOUNT STEEL CO.	CLEVELAND, OH.		7000	0	0	0	0	840	7000	7000	7000	7000	7000
INLAND STEEL	SHARON, PA.		2100	0	0	0	0	0	0	0	2100	2100	2100
e JONES & LAUGHLIN STEEL CORP.	GARY, IN.		1500	0	0	0	0	0	0	0	1500	1500	1500
JONES & LAUGHLIN STEEL CORP.	PITTSBURGH, PA.		2788	0	0	697	1394	2091	2788	2788	2788	2788	2788
g JONES & LAUGHLIN STEEL CORP.	PITTSBURGH, PA.		2538	0	0	635	1269	1904	2538	2538	2538	2538	2538
JONES & LAUGHLIN STEEL CORP.	WARREN, OH.		6057	0	0	1514	3029	4543	6057	6057	6057	6057	6057
e NATIONAL STEEL CORP.	FAIRFIELD, AL.		10000	0	0	2500	5000	7500	10000	10000	10000	10000	10000
NATIONAL STEEL CORP.	GARY, IN.		5461	0	0	1365	2731	4096	5461	5461	5461	5461	5461
NATIONAL STEEL CORP.	PITTSBURG, CA.		6038	0	0	1510	3019	4529	6038	6038	6038	6038	6038
SHARON STEEL CORP.	FAIRLESS, PA		5885	0	0	1471	2943	4414	5885	5885	5885	5885	5885
SHARON STEEL CORP.	MARTINS FERRY, OH.		8000	0	0	0	0	0	0	8000	8000	8000	8000
e U. S. STEEL	ASHLAND, KY.		1200	0	0	0	0	0	0	1200	1200	1200	1200
U. S. STEEL	CAMPVILLE, OH.		5000	0	0	0	0	1500	3000	3000	5000	5000	5000
U. S. STEEL	CHICAGO, IL.		4000	0	0	0	0	1200	2400	2400	4000	4000	4000
a U. S. STEEL	MIDDLETOWN, OH.		5000	0	0	0	0	1500	3000	3000	5000	5000	5000
e U. S. STEEL	MIDDLETOWN, OH.		4000	0	0	0	0	1200	2400	2400	4000	4000	4000
U. S. STEEL	MIDDLETOWN, OH.		5800	0	0	0	0	2320	2320	4060	4060	5800	5800
U. S. STEEL	ST. LOUIS, MO.		3800	0	0	0	0	1520	1520	2660	2660	3800	3800
e WHEELING-PITTSBURGH STEEL	CHICAGO, IL.		3800	0	0	0	0	1520	1520	2660	2660	3800	3800
WHEELING-PITTSBURGH STEEL	DETROIT, MI.		3000	0	0	0	0	0	0	3000	3000	3000	3000
CONTRACTORS:													
BUDGET SALES, INC.	IDAHO FALLS, ID.	20	0	20	0	0	0	0	0	0	0	0	0
CYCLONE SHOPS, INC.	HUNTINGBURG, IN.	50	0	50	0	0	C	0	0	0	0	0	0
JACOBSON STEEL, INC.	MORELAND, ID.	22	0	22	0	0	0	0	0	0	0	0	0
SEVEN DAY BUILDERS	ST. LOUIS, MO.	10	0	10	0	0	0	0	0	0	0	0	0
STONYRIDGE REALTY	NEW CARLISLE, OH.	15	0	15	0	0	0	0	0	0	0	0	0
	TOTALS	1517	135117	1517	1325	11017	25594	49603	88587	116157	126957	135117	135117
	CUMULATIVE TOTALS			1517	2842	13858	39452	89055	177642	293799	420756	555873	690990

*NOTE: LETTER IN FIRST COLUMN DENOTES (g)ALVALUME, (e)LECTROGAVANIZED, OR (a)LUMINIZED PRODUCTION LINES.

maximum steel consumption would be 980 tons/day or 6860 tons/week. As seen in the material availability data, this production can be reached as early as week 2; long-term production by the major steel manufacturers far exceeds the capacity of the available K-Span equipment.

To fully take advantage of K-Span technology in the first 2 weeks of mobilization, enough material must be available through inventory and suppliers. This material is generally not stockpiled, with only 1517 tons available upon short notice. Expected shortages for week 1 would be 1325 tons. For the initial 2-week period, the expected shortage would be 4018 tons of sheet steel. This material would have to be stockpiled to ensure immediate full production.

Some lead time would be required for site preparation, foundation construction, equipment transport, and setup. However, similar delays would be expected to occur in the transportation of materials; therefore, the amount of stockpiled materials required would not be affected.

Logistics

K-Span structures are not typical preengineered or panelized construction. The building sections are not formed until time for erection at the jobsite. This approach results in significant savings in shipping volume of materials; however, special equipment is required at the jobsite.

The K-Span system is mounted on a trailer which is 30 ft long, 7.5 ft wide, and 7.5 ft high. Gross weight is 16,000 lb. Runout tables and seamers are transported on the trailer. All other equipment is considered standard for construction and therefore not included in assessing the logistics of the system.

Cost

The only difference between K-Span system and conventional construction methods is in fabrication of the structural shell. Most other aspects are the same with regard to cost and construction. Some building components, such as suspended lighting or sprinkler systems, will adapt readily to the K-Span configuration, whereas other systems, such as doors and windows in the curved sidewalls, would take considerably more time to install, increasing costs. It is not possible to consider all conditions within the scope of this report. Instead, the designer should realize that the system has certain limitations and that the most efficient K-Span structures will be designed within these limitations. Familiarity with the system is therefore important in minimizing cost.

The cost of the entire K-Span system and equipment listed in the first part of Table 1 is approximately $150K. To build K-Span structures, the equipment can be purchased, leased, or the project can be awarded to an independent contractor. For small projects, it is more efficient to contract for the structure. If, however, the system were to be used at full capacity (potentially by Government personnel in a mobilization situation), it would be more cost-effective to own the machines.

Table 6 shows a cost estimate to contract for a 50 ft by 70 ft by 18 ft bare structure. The estimate is based on past projects and information provided by steel producers and contractors. It is to include one overhead door, two personnel doors, and three wind-driven turbine ventilators, and is to be built on a preleveled surface (floor slab not included). Labor costs were estimated at $25/hr for a construction effort of 300 manhours. Sheet steel price is $0.45/lb. The caisson and bond beam foundation cost about $27/lin ft. Approximate total cost is $10/sq ft. Materials alone for the structure cost about $5.75/sq ft.

Table 6

Cost Estimate for a 50 by 70 by 18 ft K-Span Structure

Items	1988 Dollars
Engineering	500.00
Door Frames	400.00
Hardware	380.00
Sheet Steel	9,970.00
Foundation	6,500.00
Overhead Door	1,960.00
Personnel Doors	700.00
Ventilators	300.00
Labor	7,500.00
Equipment Rental	1,200.00
Fuel	500.00
Travel	1,000.00
Overhead and Profit	3,500.00
	34,410.00
Bond	516.51
TOTAL	34,926.51

4 STRUCTURAL INTEGRITY AND MATERIAL DURABILITY

Structural Analysis

A detailed analysis of the standard K-Span configuration was performed through both numerical analysis and physical testing. The objective was to determine the collapse loads of these structures under snow and wind loading conditions. Details of the numerical analysis for the K-Span shell are reported in USACERL TR M-88/01. Results of the analysis showed that local nonlinearities (i.e., local buckling) would govern the ultimate load conditions through the formation of hinges leading to collapse of the structure.

The effects of localized nonlinearities were therefore determined by testing (1) panel sections of the shell and (2) complete arch sections of the structure under a line load. Possible collapse mechanisms resulting from local buckling and the corresponding bounds for the collapse loads of the structures were determined.

It should be noted that, for the analysis of Super-Span and Econo-Span structures, local buckling was not expected to be a problem. Their cross sections are close to a standard tangent and arc corrugated profile, without the vertical web seamed at the top. An analysis of this type of profile has been presented by Abdel-Sayed, et al.[6].

Critical Moments and Local Buckling

To investigate the type and the relative importance of the localized nonlinear effects developed under high circumferential moments, it was decided to laboratory-test an arc of a typical panel for an intermediate-sized building. The 50 ft by 18 ft structure was used for this study. A straight panel was also tested.

The axial stresses developed perpendicular to the panel cross section under a moment field are the moment fiber stresses. These stresses are expected to result in the same type of localized nonlinear effects as in the case of the full arch shell structure. To determine the critical moments at the fixed base, the panel-beam was tested as a cantilever beam; for the critical moments away from the base, the panel-beam was tested as a simply supported beam. Since compressive stress can develop either in the top fibers (seam) or the lower fibers (flange) of the typical panel (Figure 1), two cases were tested: one with the load applied upward (negative moment) and another with the load applied downward (positive moment).

Test Apparatus. Strain measurements were made using electrical resistance strain gauges (Micro-Measurements, Inc., Model EA-06-125AD-120). Deflection readings were measured with linear voltage displacement transducers (LVDTs) from Celesco Transducer Products, Inc. (Model PT-101-60A). Data were recorded using Endevco signal conditioners, Model 4470, a Hewlett Packard 3455A digital voltmeter, and a Hewlett Packard desktop computer (Model 9825A).

A constant rate of load was applied for the simply supported and cantilever beam tests. Hydraulic rams were controlled by the following Material Testing System, Inc. (MTS) equipment: load cell, 50,000-

[6] G. Abdel-Sayed, et al., "Cold-Formed Steel Farm Structures, Part II: Barrel Shells," *American Society of Civil Engineers, Proceedings, Journal of the Structural Division*, Vol 111, No. 10 (1985), pp 2090-2104.

lb/capacity, Model 661.22, Material Testing System Model 810; digital ramp generator, Model 415; controller, Model 422; digital indicator, Model 430; and Master Control Panel, Model 413. For the complete arch tests, a constant rate of deflection was applied using a screw-type loading system. Load was measured for the complete arch tests by two load cells, BLH Model U3L, 10,000-lb capacity. The load and deflection data for all tests are tabulated in the Appendix.

Cantilever Beam Tests. Test specimens were 54-in.-long sections of the four-panel curved cross section shown in Figure 5. One end was set in a reinforced concrete beam to form the fixed end. The concrete beam and panel assembly were bolted to the load frame. Load was applied to the free end. Figure 6 shows details of the load and support conditions as well as the location of deflection gauges. Strain gauge locations are shown in Figure 7.

Positive Moment. Three tests were run to determine the positive buckling moment at the fixed end. In the first two tests, severe relative displacement was observed in the free (cut) edge of the panel which appeared to contribute to buckling of the section (Figure 8a). To reduce this effect, additional bracing was applied in test 3 by attaching 1-1/2 by 1-1/2 by 1/8 in. angles at discrete points along the beam as shown in Figure 8b.

Results for the three tests are tabulated in the Appendix. Figure 9 shows load deflection plots. In all cases, failure occurred in an outer seam, having a free (cut) edge adjacent to the buckled section. As load approached the ultimate, severe local deformation was evident in the region of the free edges. Test 3, with the angle bracing, had the highest ultimate load and is probably the most accurate representation of a continuous structure. The average ultimate moment was 3052 in.-lb/in.

Strain data from the corrugated portion of the cross section was inconsistent and indeterminate. Compressive strains in the flat seam indicate that, in all tests, yielding was reached at failure of the section. This condition is expected in the case of a fully braced section for which local buckling cannot occur.

Negative Moment. Three tests were performed to determine the negative buckling moment of the section at a fixed end. Test results are tabulated in Appendix A. Load-deflection curves are shown in Figure 10. Failure occurred by buckling of the flange, always near the fixed end (Figure 11). Ultimate moments for the three tests were consistent, with an average of 2,525 in.lb/in.

Tensile strains measured at the seam varied significantly in the three tests. Stresses calculated from the strain data vary from 25.4 ksi in test 2 to 52.7 ksi (yield stress) in test 3. The variation was probably due to nonuniform load distribution and local effects at the fixed end. The average ultimate stress for the three tests was 37.9 ksi.

Simply Supported Beam Tests. Three cross sections of simply supported beams were tested under various conditions. The single-panel straight, single panel curved, and four-panel curved cross sections are depicted in Figure 5. All three cross sections were tested due to the potential effects of the corrugations and free edges. Eight-foot sections were supported in the 6-ft test frame (6-ft simply supported length) and loaded at 1/3 points, as shown in Figure 12.

Various bracing was used to enforce boundary conditions of the beams. To restrict the free edge from excessive warping, 1-1/2 by 1-1/2 by 1/8 in. T-sections were attached to the flange at the load application and support points (Figure 13a). Most beams were also braced at the ends to prevent twisting and warping (Figure 13b). Beams with unbraced ends were also tested to determine the effect of the bracing. Table 7 summarizes the number of tests run for each configuration. Locations of strain and deflection gauges are shown in Figure 14.

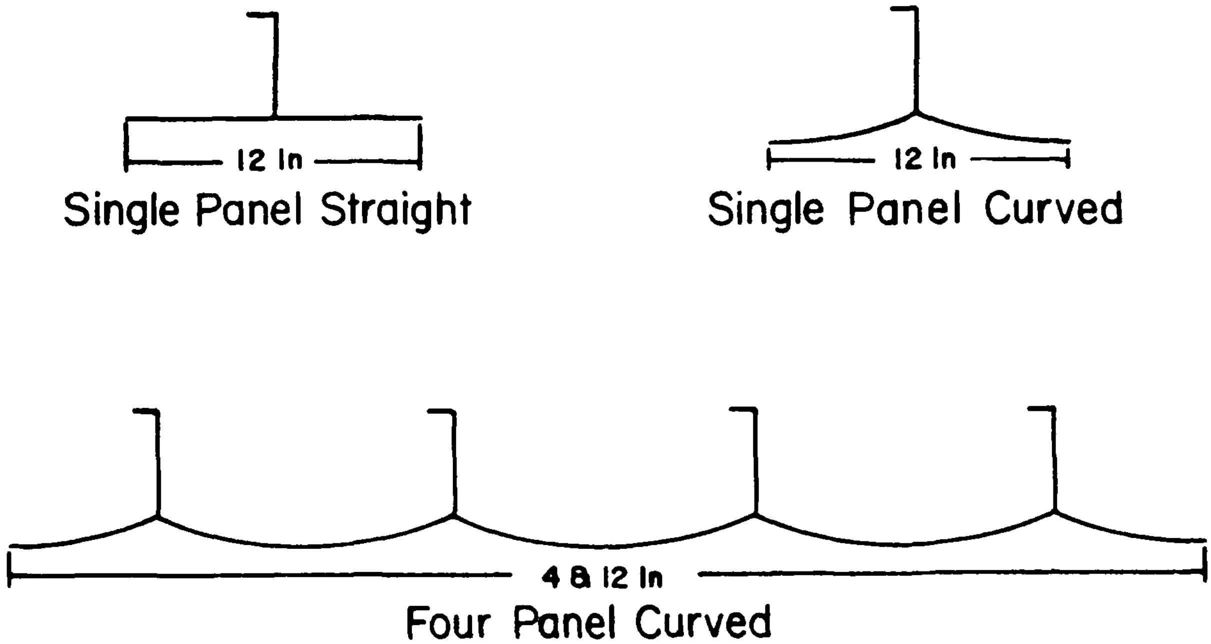


Figure 5. Test specimen cross sections for the (a) single-panel straight, (b) single-panel curved, and (c) four-panel curved test configurations.

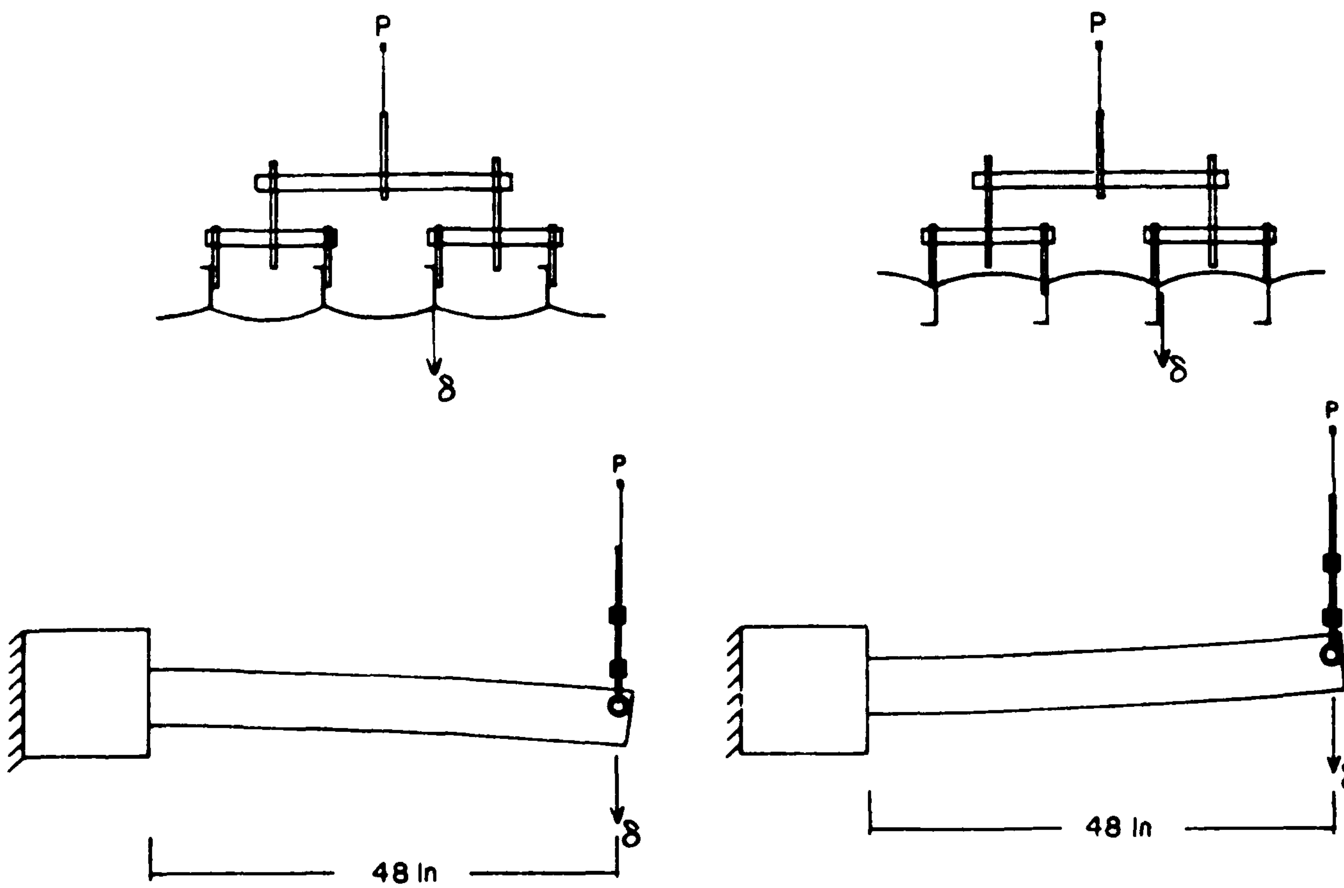


Figure 6. Load and support conditions and deflection gauge locations for the cantilever beam tests in (a) positive moment and (b) negative moment.

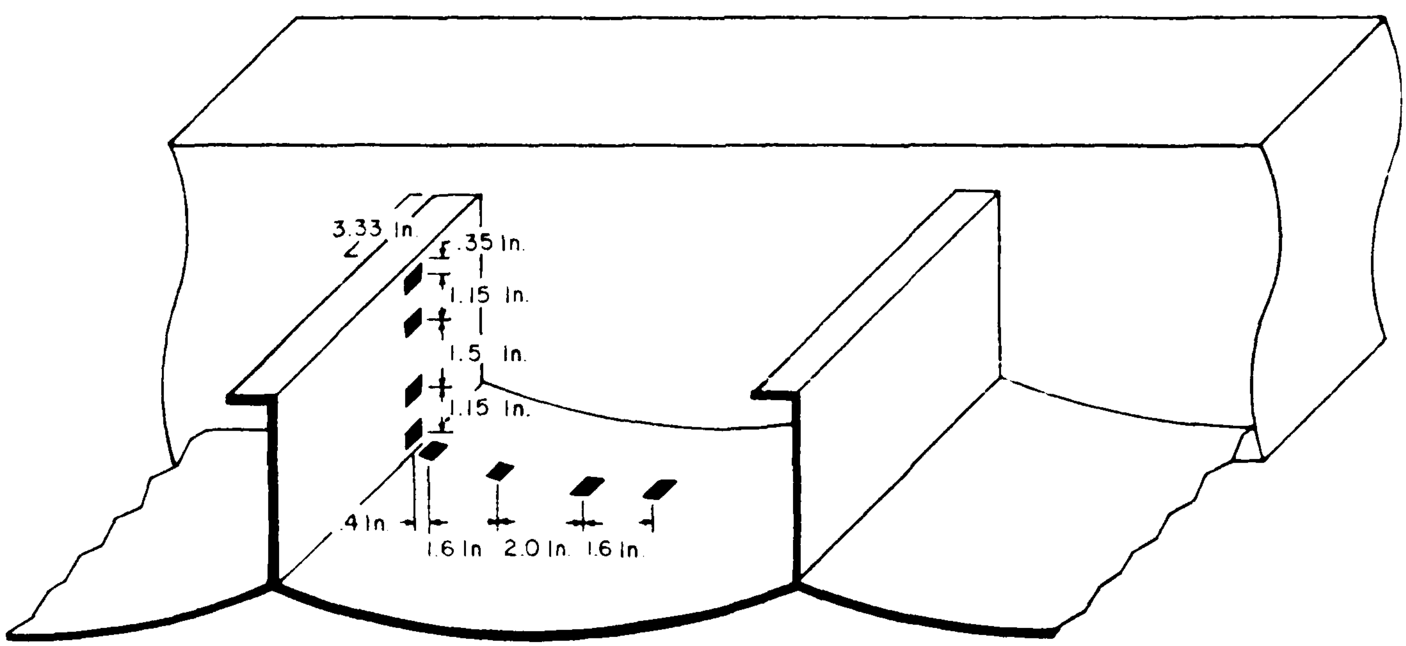
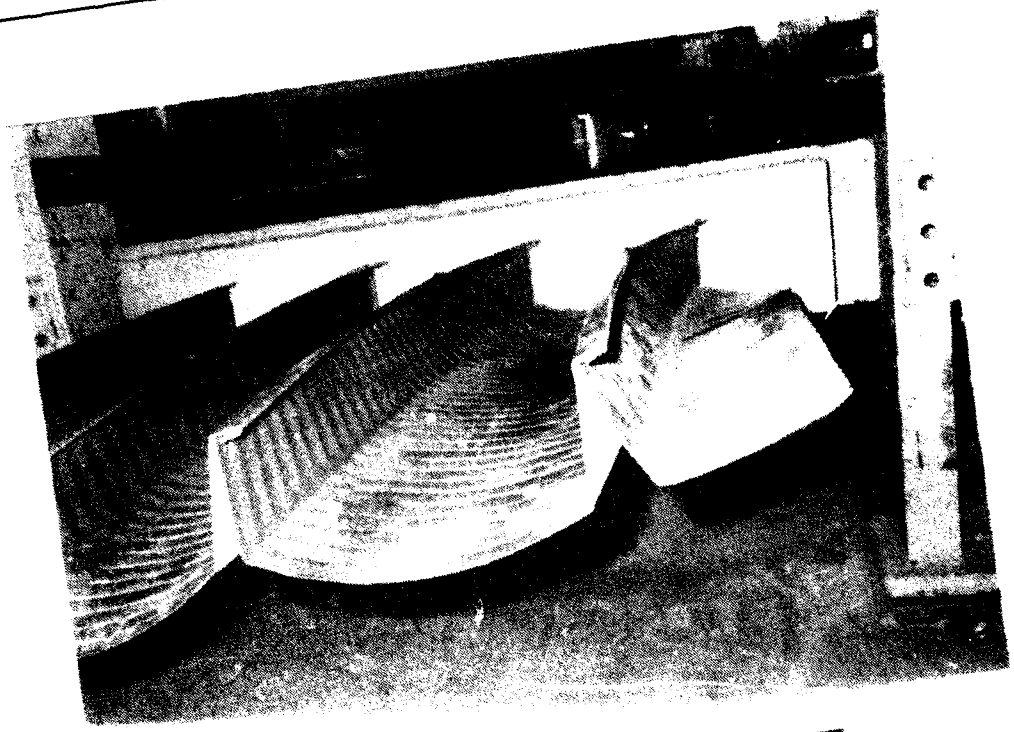


Figure 7. Strain gauge locations for cantilever beam tests.



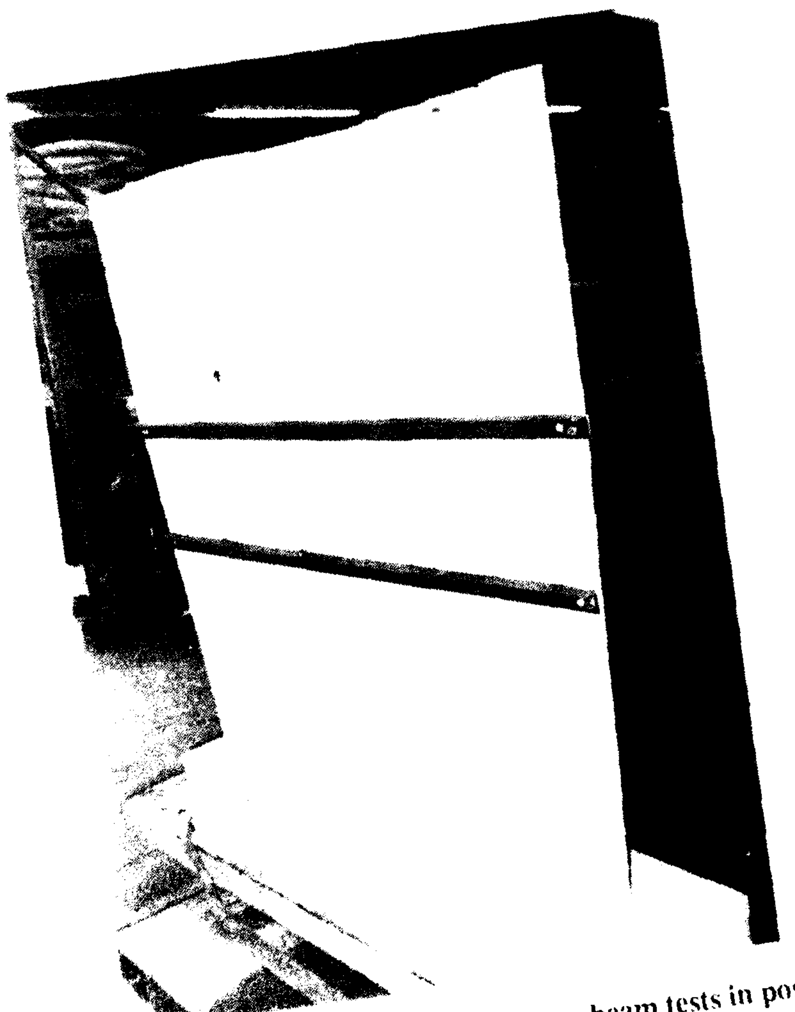


Figure 8. (a) Distortion of the free edge of the cantilever beam tests in positive moment and (b) 1-1/2-in. angle bolted to the free edge to reduce distortion.

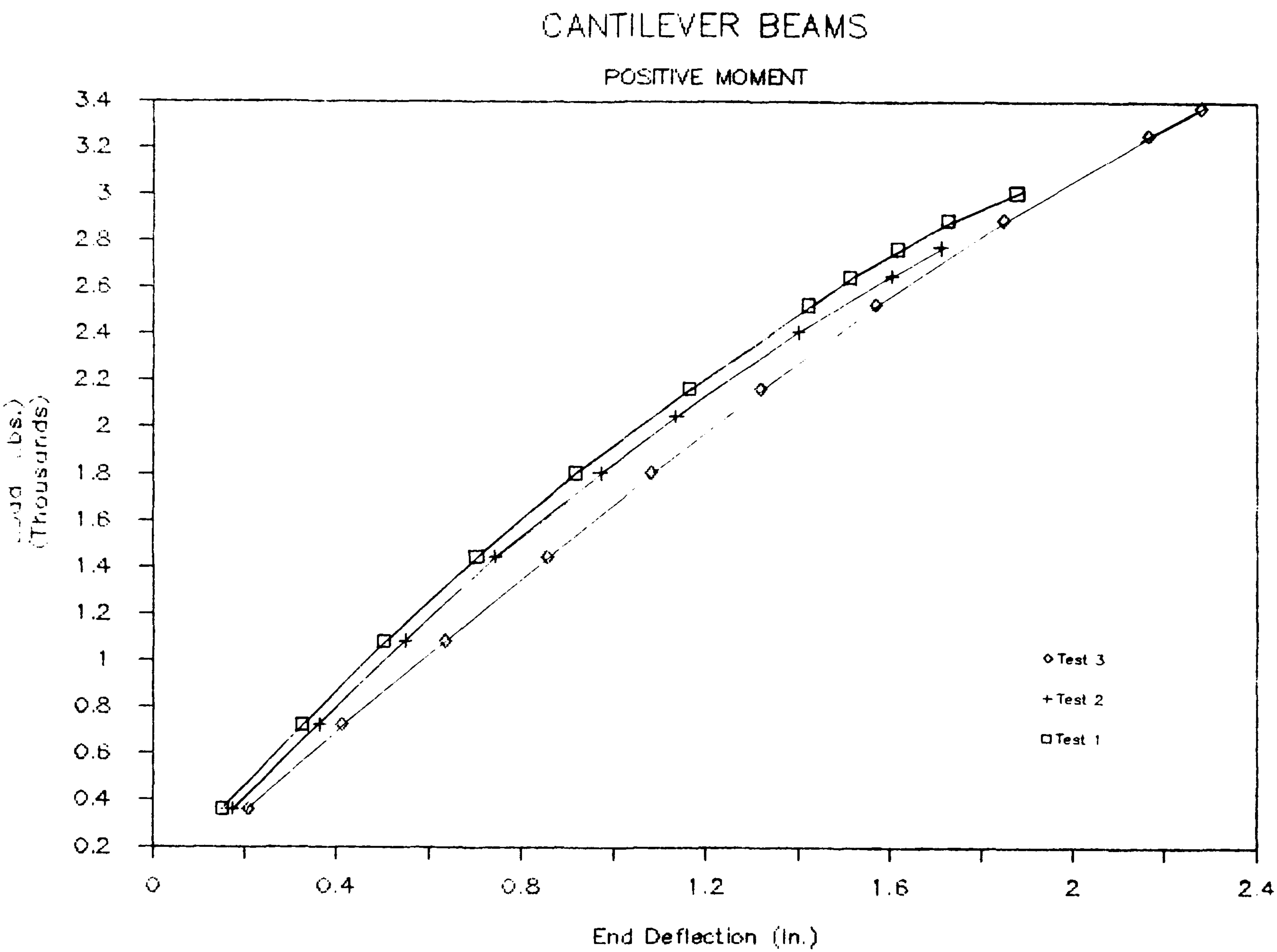


Figure 9. Load deflection curves for the cantilever beam test, positive moment.

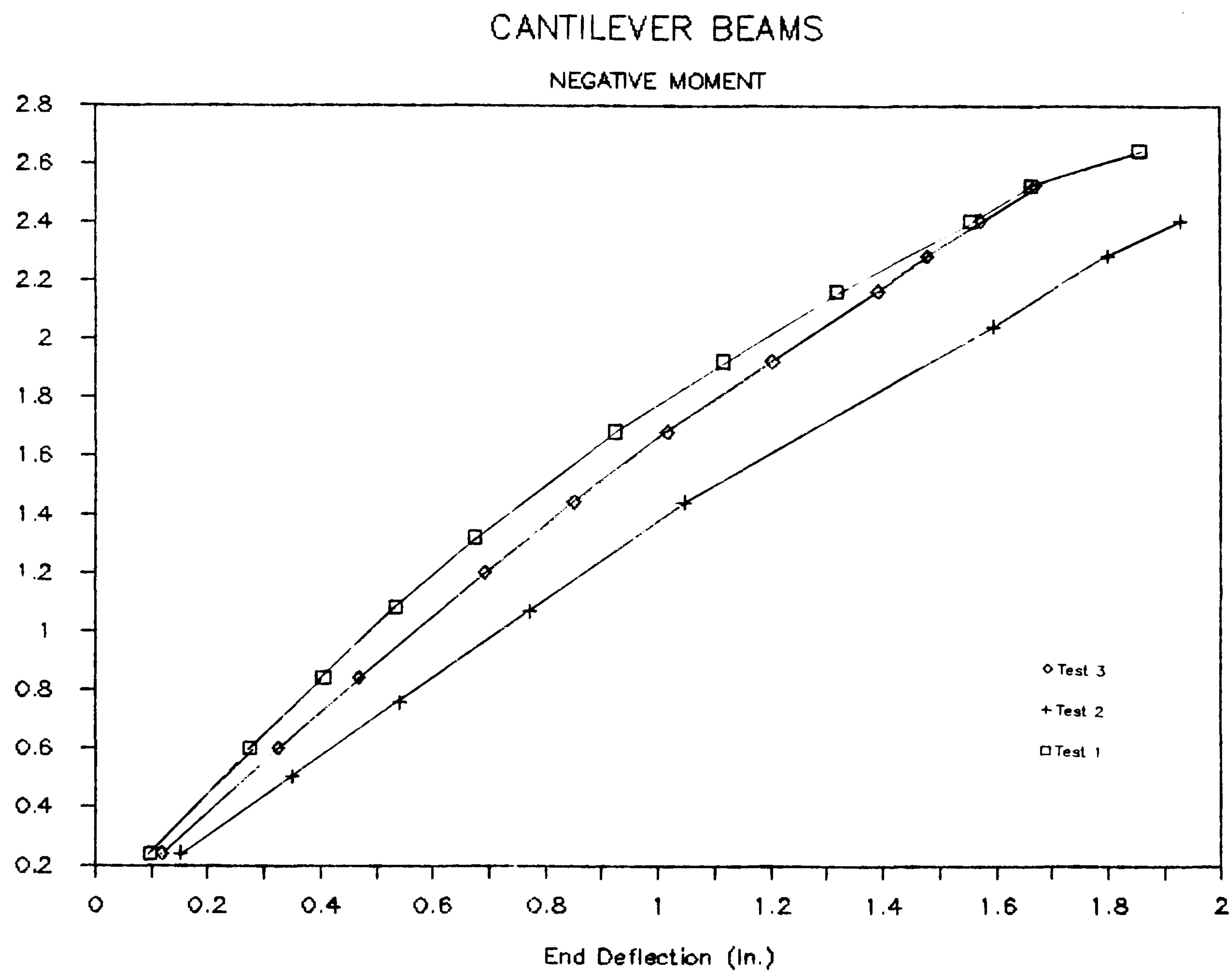


Figure 10. Load deflection curves for the cantilever beam tests, negative moment.

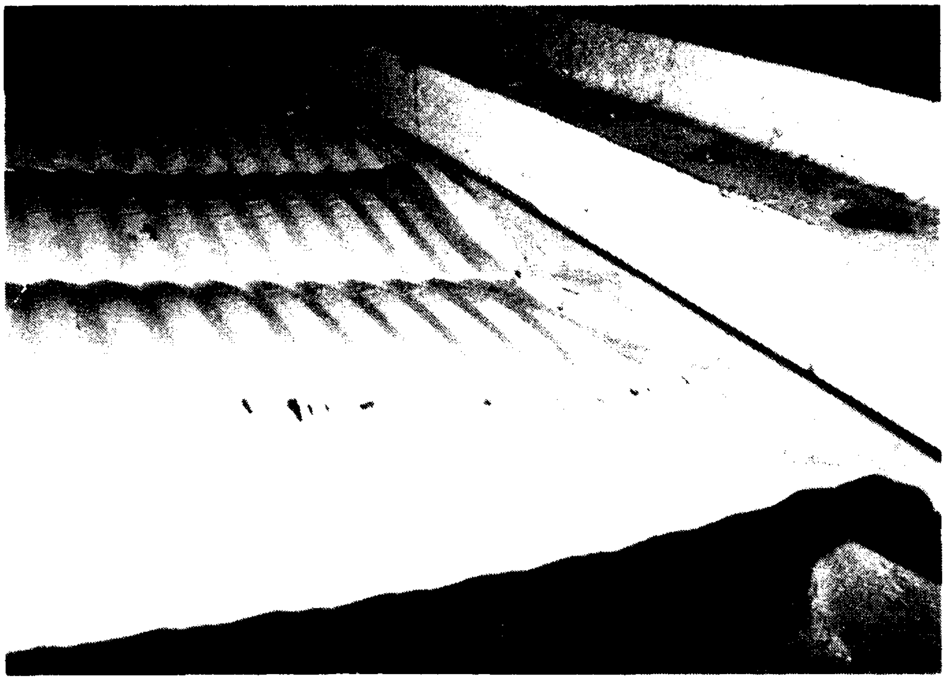


Figure 11. Buckling of the cantilever beam tests, negative moment.

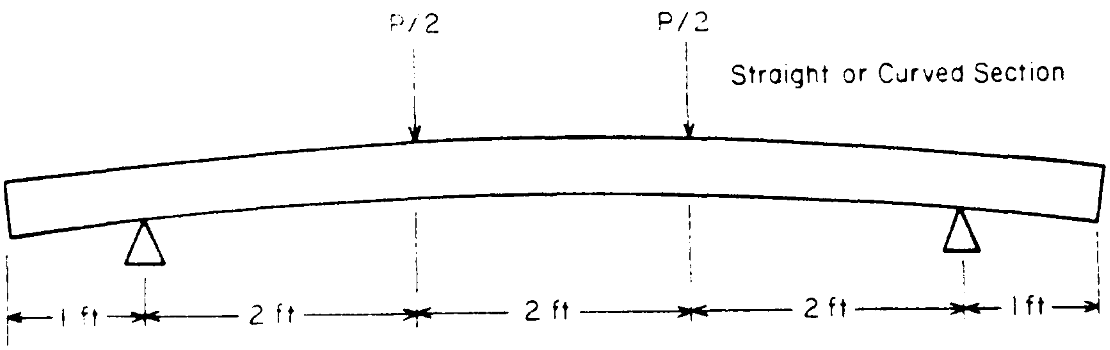


Figure 12. General configuration, simply supported beam tests.

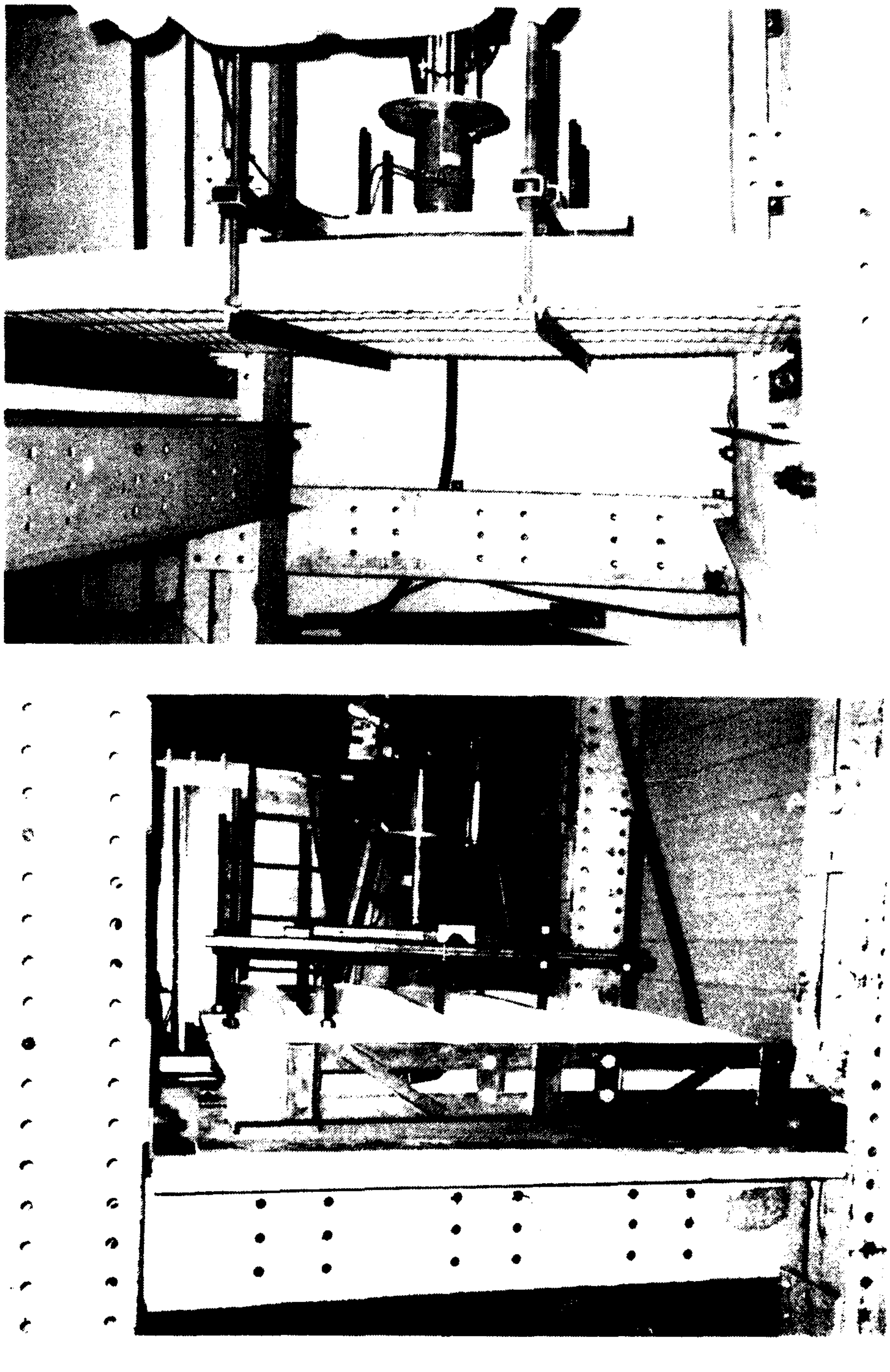


Figure 13. Additional bracing configurations of the simply supported beam tests: (a) T-sections bolted to free edge and (b) end bracing bolted to each web.

Table 7

Summary of Configurations for the Simply Supported Beam Tests

Cross Section	Moment	Tests	Load Rate	Notes
Single Straight	Positive	1	100 lb/min	
	Negative	1	100 lb/min	
Single Curved	Positive	2	100 lb/min	Web braced, test 1
	Negative	2	100 lb/min	
Four-Curved	Positive	5	1000 lb/min	No end bracing, tests 3,4
	Negative	3	1000 lb/min	No end bracing

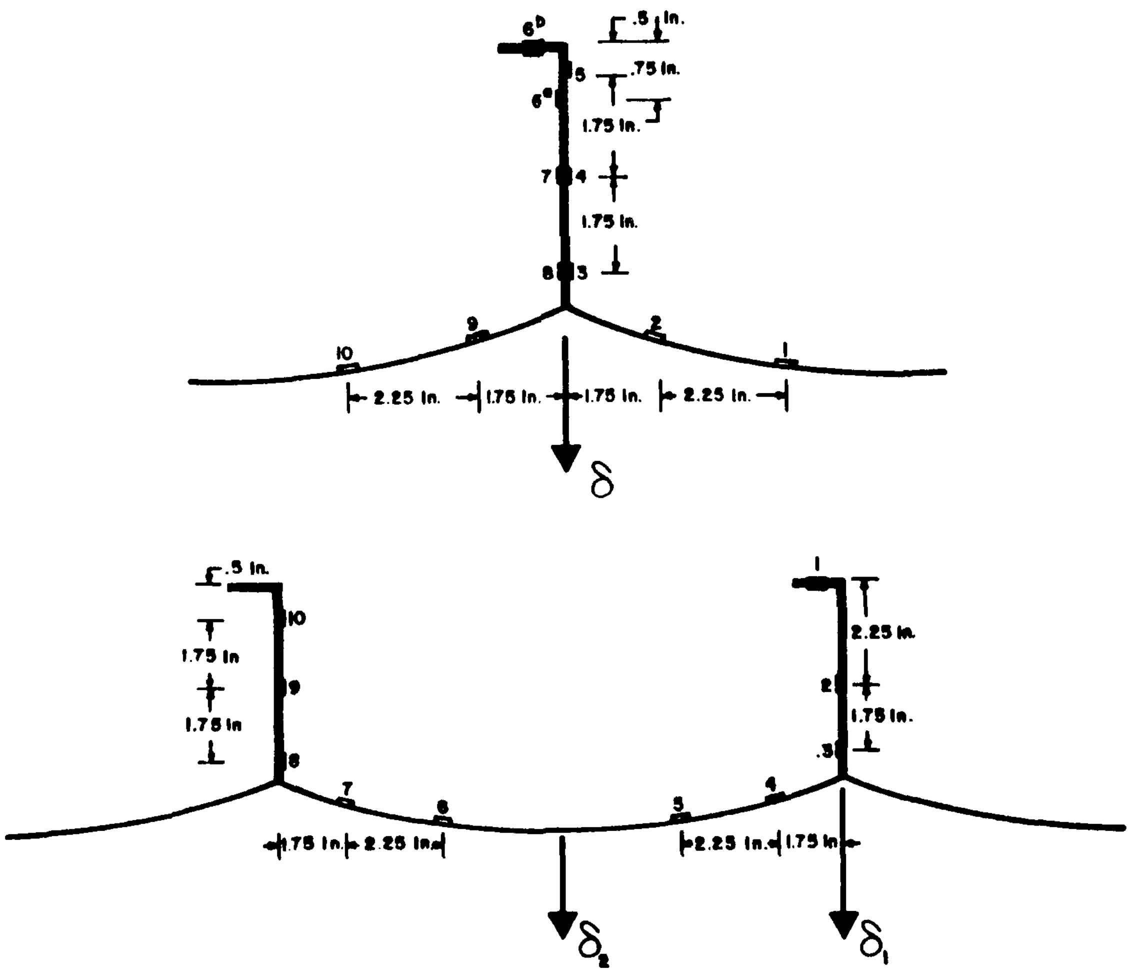


Figure 14. Strain and deflection gauge locations for (a) single-panel and (b) four-panel simply supported beam tests.

Positive Moment. In general, results of the simply supported beams in positive bending were inconsistent and inconclusive. This outcome is probably attributed to the sensitivity of the mode of failure to initial imperfections and local deformations due to load configuration. Figure 15 shows the load-deflection curves for all tests. Failure always occurred by local buckling of the seam. In the single-panel beam tests, lateral buckling of the web and seam occurred, rotating about the base of the web as shown in Figure 16. This behavior has been predicted by Yu[7] in an analysis of a similar configuration without curvature and minor corrugations.

The single straight panel was relatively stiff, showed good consistency in the two tests, and had a relatively low average ultimate moment of 2512 in.-lb/in. Strains through the depth of the cross section at mid-span were approximately linear at a load of 2008 in.-lb/in. The compressive stress for the section seam at ultimate moment was 30.4 ksi.

In test 1 of the single curved panel, the web was supported laterally at the load points, giving an unbraced length of 24 in. This condition resulted in a stiffness close to the single-panel straight beam, but nearly twice the ultimate bending moment. When the lateral support was removed in test 2, the maximum deflection nearly doubled; however, ultimate load remained about the same. The average ultimate moment for the two tests was 4835 in.-lb/in. Strain data for the corrugated portion of the cross section were inconsistent and inconclusive. Ultimate stress measured in the seam was 47.7 ksi (very near yielding) in test 1, whereas the material yielded in test 2.

Five tests were performed on the four-panel cross section. Three tests used end bracing and two were unbraced; however, the end bracing did not appear to have an effect on the test results. The results did vary significantly with respect to both stiffness and ultimate strength. Failure of these sections occurred through local buckling of the seam, with only very slight lateral displacement of the seam and web (Figure 17). As soon as one seam buckled, at least one other seam failed before the loading equipment shut down automatically. Ultimate moments were extremely high in all tests, ranging from 4200 to 6900 in.-lb/in. Strain readings taken during the test indicate that the stresses in the seam at failure were yield stresses. This finding is consistent with the type of local failure observed.

Negative Moment. In general, the load-deformation and ultimate moment results of all test configurations for simply supported sections in negative bending were consistent (Figure 18). Only the first curved single-panel test, in which the load application method seriously deformed the flange, varied significantly. The load application method was revised to prevent this condition from recurring. Failure occurred in all tests through local buckling of the compression flange. Severe local deformations were obvious in the free edge of the panels prior to failure (Figure 19).

The straight single-panel configuration again was the stiffest, indicating some role of the minor corrugations in reducing panel stiffness. Strain across the section of the straight panel at mid-span at a moment of 3827 in.-lb/in. again showed approximate linear distribution through the web; however, non-linear strain in the compression flange was indicative of the large local deformations observed. Tensile stress measured in the seam at failure was 38.6 ksi.

In the corrugated panels, strain data measured on the corrugated surface were again inconclusive. Tension stresses measured on the flat seam of the single panels at ultimate moment were 34.1 and 40.4 ksi in tests 1 and 2, respectively. Test 1 of the four-panel configuration showed an ultimate stress of 39.2 ksi in the seam.

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[7] Wei-Wen Yu, *Cold-Formed Steel Structures* (McGraw-Hill, 1973).

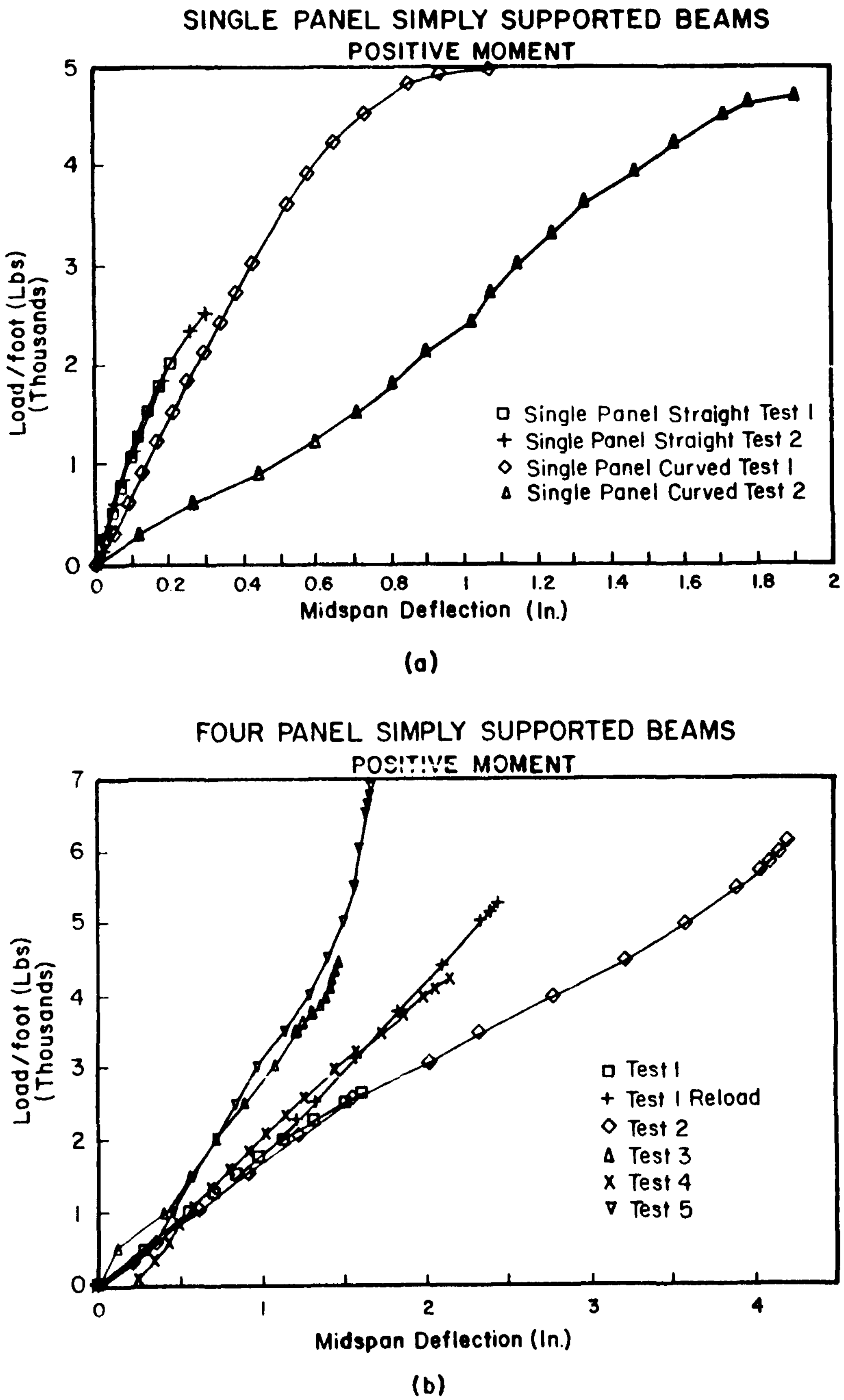

Figure 15. Load-deflection curves for (a) single-panel and (b) four-panel simply supported beam tests, positive moment.

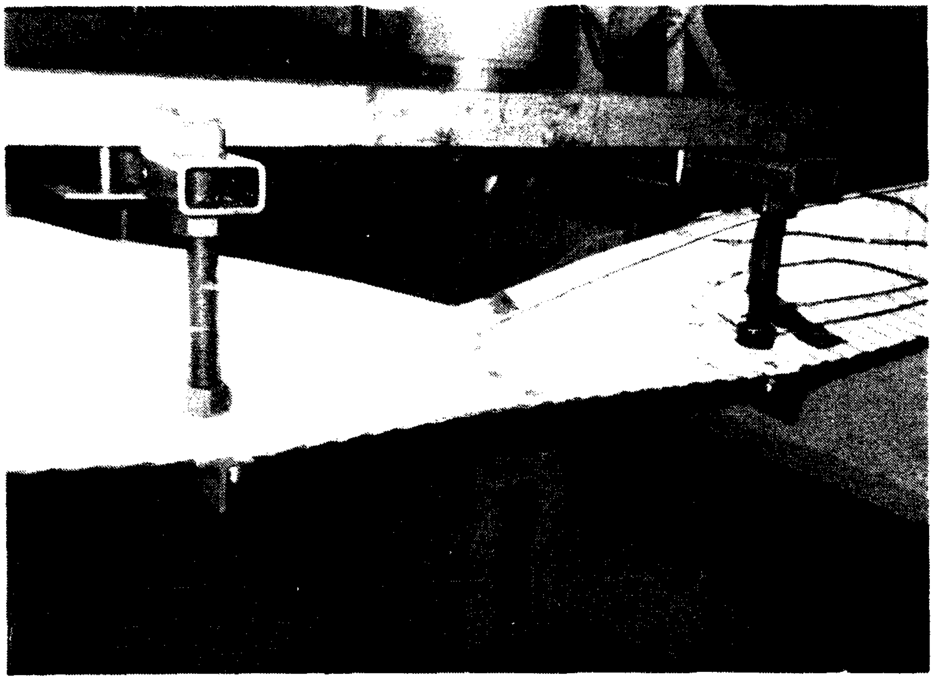

Figure 16. Typical lateral buckling of the web and seam in positive moment.

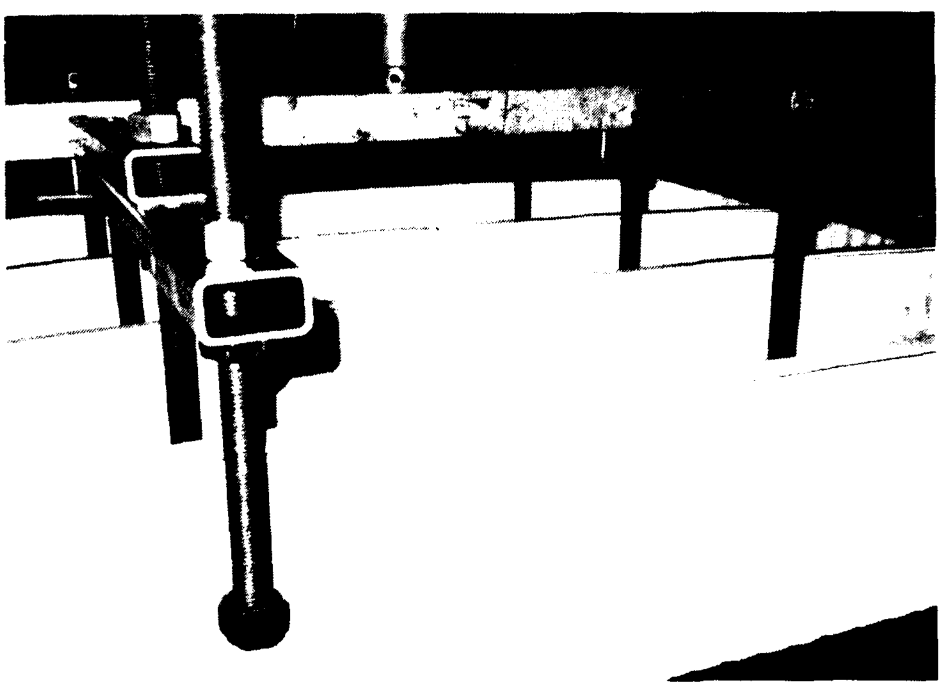

Figure 17. Failure of the four-panel simply supported beam tests, positive moment.

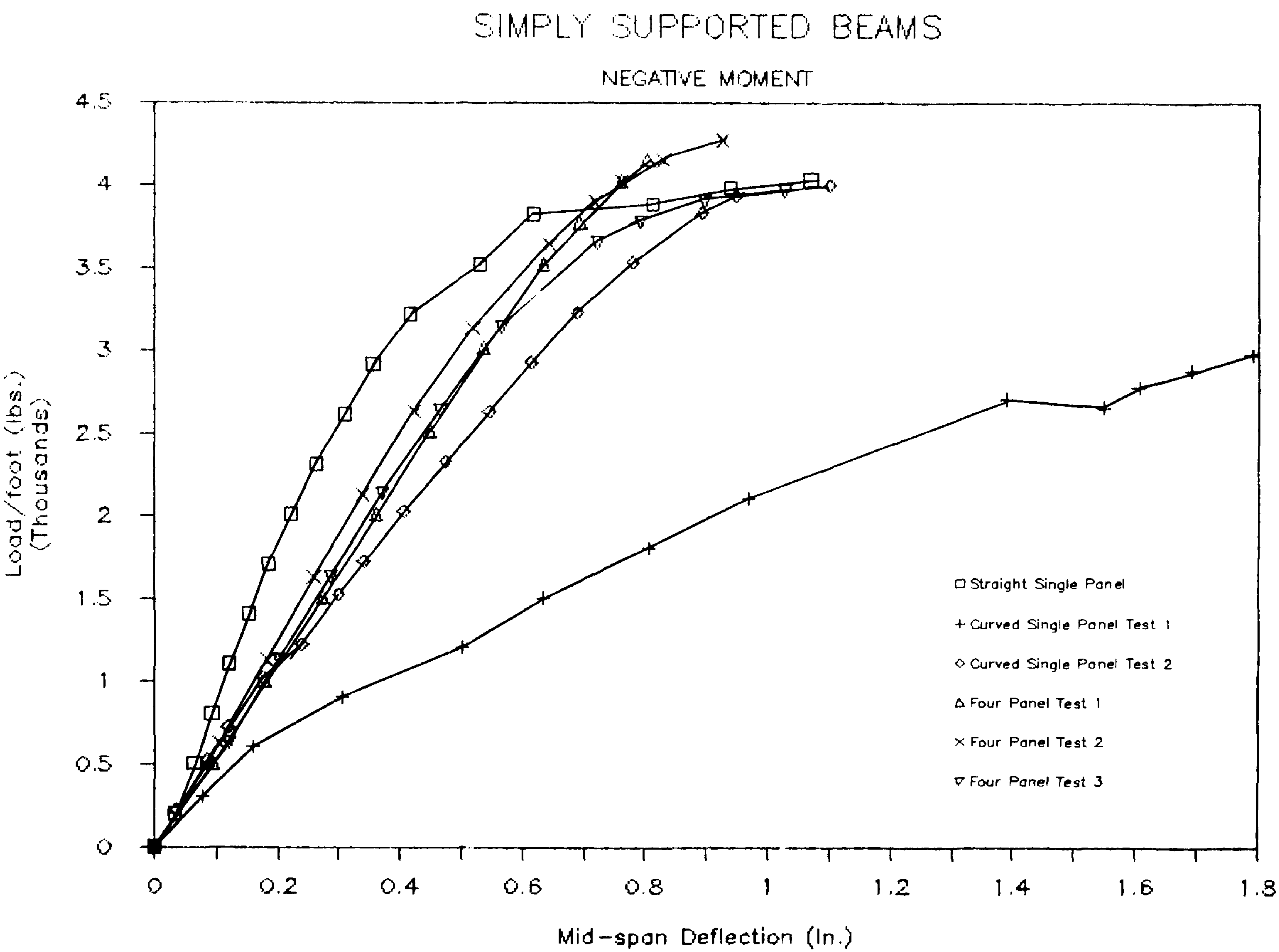

Figure 18. Load-deflection curves for all simply supported beam tests, negative moment.

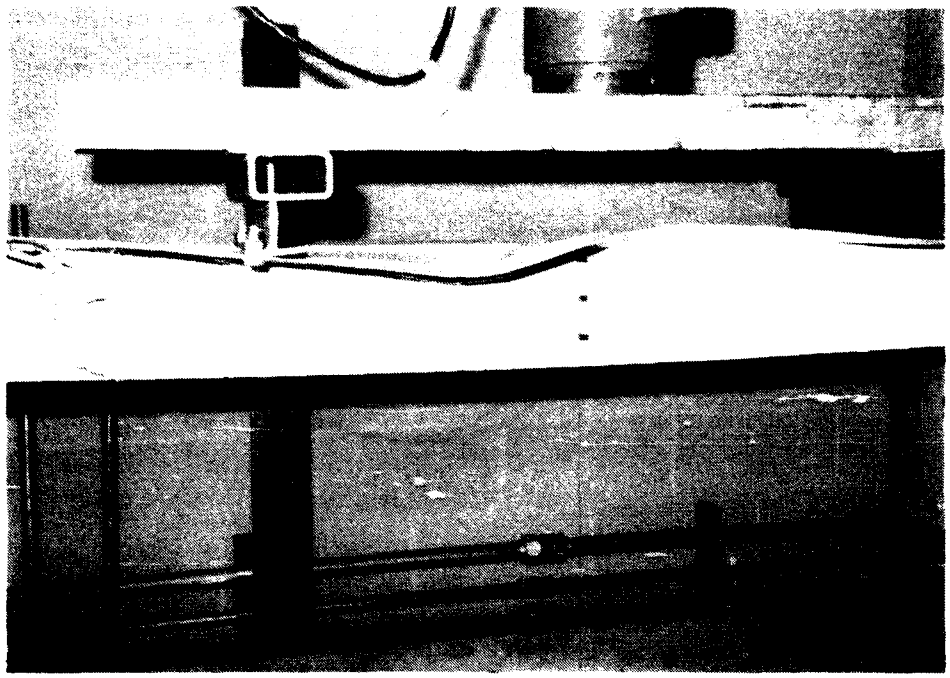

Figure 19. Deformation of the free edge of the simply supported beam under negative moment prior to failure.

Test 3 of the four-panel sections used no end bracing, which had no measurable effect. Average buckling moment for the simply supported beams in negative bending (excluding test 1 of the curved single panel) was 4087 in.-lb/in.

Complete Arch Tests. This series of tests was done to assess overall behavior of the arch structure and to further evaluate the critical buckling moment of the section. Arches were formed according to the specifications for a 50 ft wide by 18 ft high structure. The specimen was formed with the same cross section as used in the four-panel curved beam and cantilever tests.

The base of the arch was encased in a concrete beam bolted to the load frame to provide a fixed-end condition. Lateral support was required to prevent side sway of the arches, especially prior to setting of the concrete beam. Roller plates bearing on smooth plywood sheets were attached at five discrete points along each side of the arch to restrict lateral movement. Also attached at the five points were the 1-1/2 by 1-1/2 by 1/8 in. T-sections to reduce local deformations of the free edges as were used in the beam tests (Figure 20).

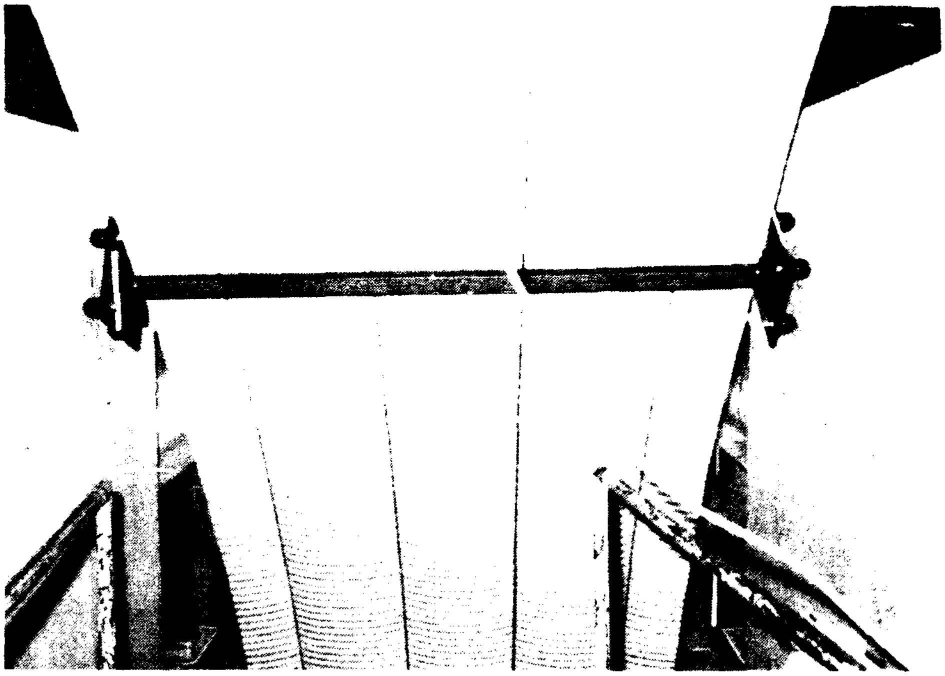

Figure 20. Roller plate and T-sections to prevent side sway and reduce load deformations of the free edge in the full arch tests.

A line load was applied at mid-span using screw loading to give a constant rate of deflection. Loading was stopped for observation of significant events during the test. The load rate was approximately 1 in./min. Load application changed slightly between tests to adjust for problems observed during testing. Also, locations of strain and deflection gauges were changed in order to record significant events and information. Configurations of all tests are shown in Figures 21 and 22. Three tests were performed; however, results for test 1 were inconclusive. Results of tests 2 and 3 are tabulated in the Appendix. All moment calculations are made using the orthotropic finite element model in a nonlinear analysis that had been developed for the numerical analysis[*].

Failure in all tests was during positive bending at the load application points by lateral buckling of the web and seam (Figure 23). The lateral buckling behavior was similar to the single-panel beam test failures, as opposed to the four-panel beam tests which buckled in the seam with no significant lateral displacement.

In test 1, a single loading screw allowed for severe twisting of the cross section at mid-span. This action resulted in premature buckling of the outer web and seem. It was clear that a load method to control twisting of the cross section was needed.

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* D. Briassoulis, et al.

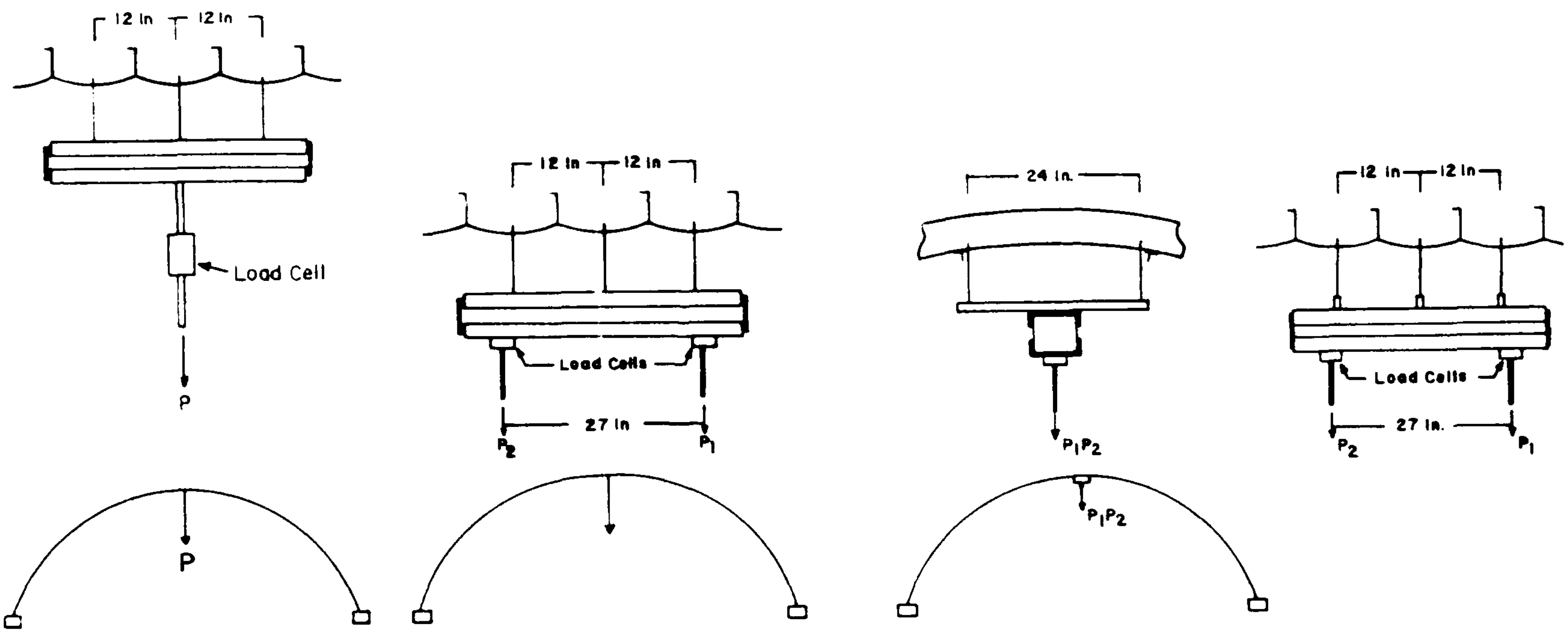

Figure 21. Test configurations for full arch tests (a) 1, (b) 2, and (c) 3.

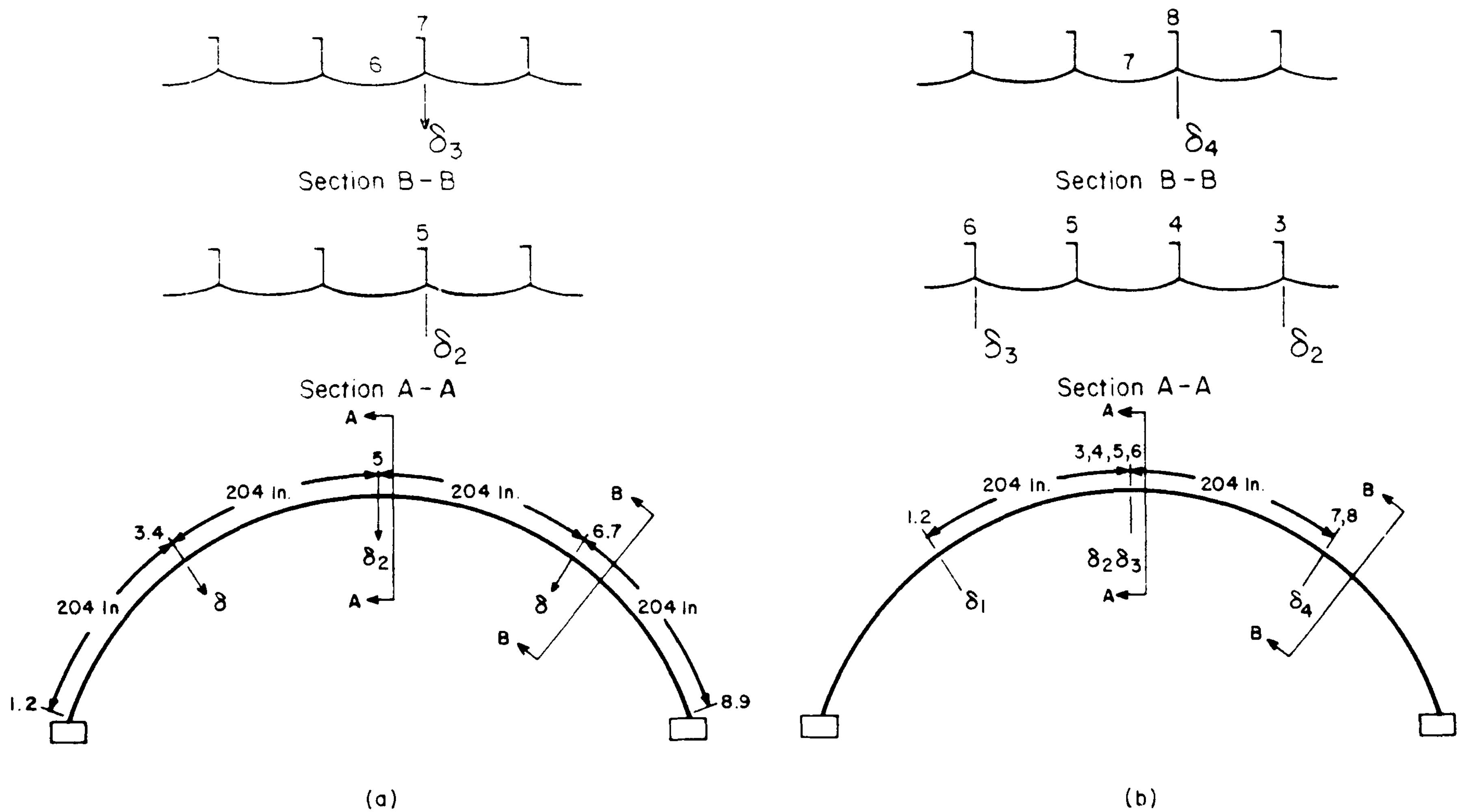

Figure 22. Strain and deflection gauge locations for full arch tests (a) 2 and (b) 3.

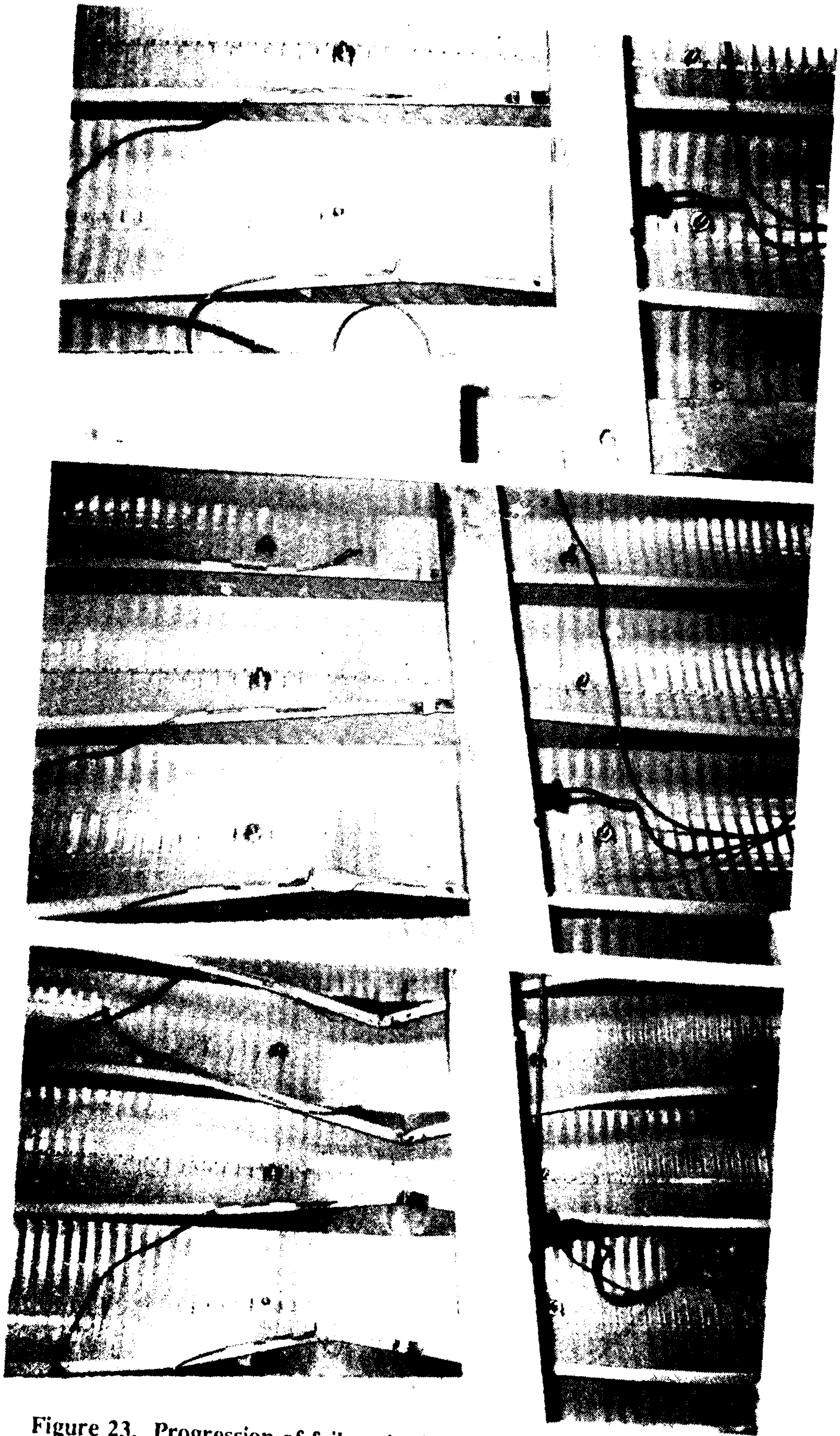

Figure 23. Progression of failure in the full arch, positive moment.

In test 2, two loading screws were used to maintain uniform deflection of the cross section. Unexpectedly, a nonuniform load had to be applied to achieve this condition. The "weak side" of the cross section was the same as observed in full arch test 1 and is shown in Figure 24. Also, it should be noted that the seam to fail first was the same as in all of the cantilever beam tests. The progression of failure across the section is shown in the series of photographs taken during full arch test 3 (Figure 23).

It was expected that, in positive bending, all seams would buckle in the same direction, toward their sheer center.[9] Instead, the direction in which the individual seams rotated was apparently affected by the locations of the applied loads. All seams buckled toward the center of the cross section (Figure 23).

In test 3, the load was further distributed into two line loads, 1 ft to either side of mid-span, to reduce local deformations. This was the same load spacing used in the four-panel beam tests. Although test 3 did have the highest ultimate load and moment, the behavior was identical to test 2, demonstrating the same "weak side" characteristic.

Ultimate load in both tests actually came after local buckling had occurred in the outermost seam on the weak side. This result indicates that asymmetry of the cross section due to the direction of the seam may have allowed premature failure of the section. Ultimate loads on the weak and strong sides were 492 and 771 lb (plus the 450-lb weight of the load apparatus) in test 2, and 743 and 954 lb in test 3. The average moment across the section at these loads using a linear elastic computation was 1372 in.-lb/in. for test 2 and 1708 in.-lb/in. for test 3.[10] The load-deflection curves are shown in Figure 25.

Loading was continued after initial failure, requiring a constant load (lower than the ultimate load) to deflect the structure until the arch buckled in negative bending at the quarterpoint (Figure 26). Due to displacements of the arch in the load frame after the initial failure, the negative moment assessment based on load is not considered accurate; however, approximate ultimate moments are 1300 and 2000 in.-lb/in.[11]

Strain readings from the seam at both mid-span and quarterpoint gave an indication of the stresses at failure. At ultimate moment of the mid-span in positive bending, the compressive stresses were measured as 30 and 26.2 ksi. At quarterpoint buckling in negative bending, tension stresses in the seam were 39.8 and 33.3 ksi.

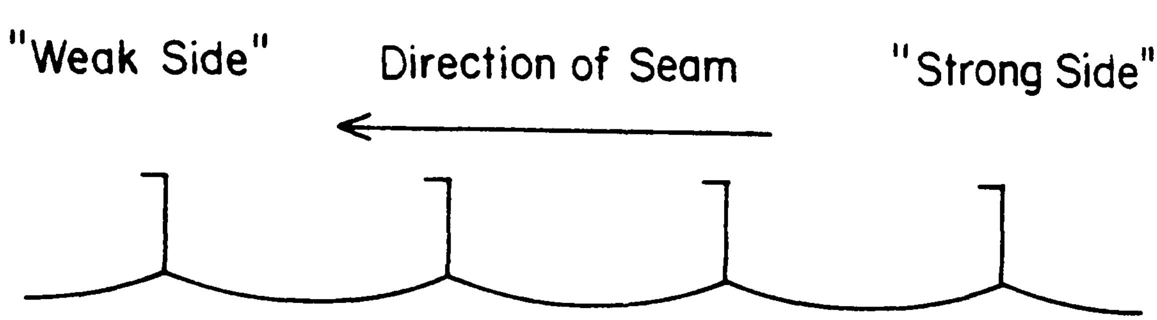

Figure 24. "Weak side" of the four-panel cross section observed in testing.

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[9] Wei-Wen Yu.

[10] D. Briassoulis, et al.

[11] D. Briassoulis, et al.

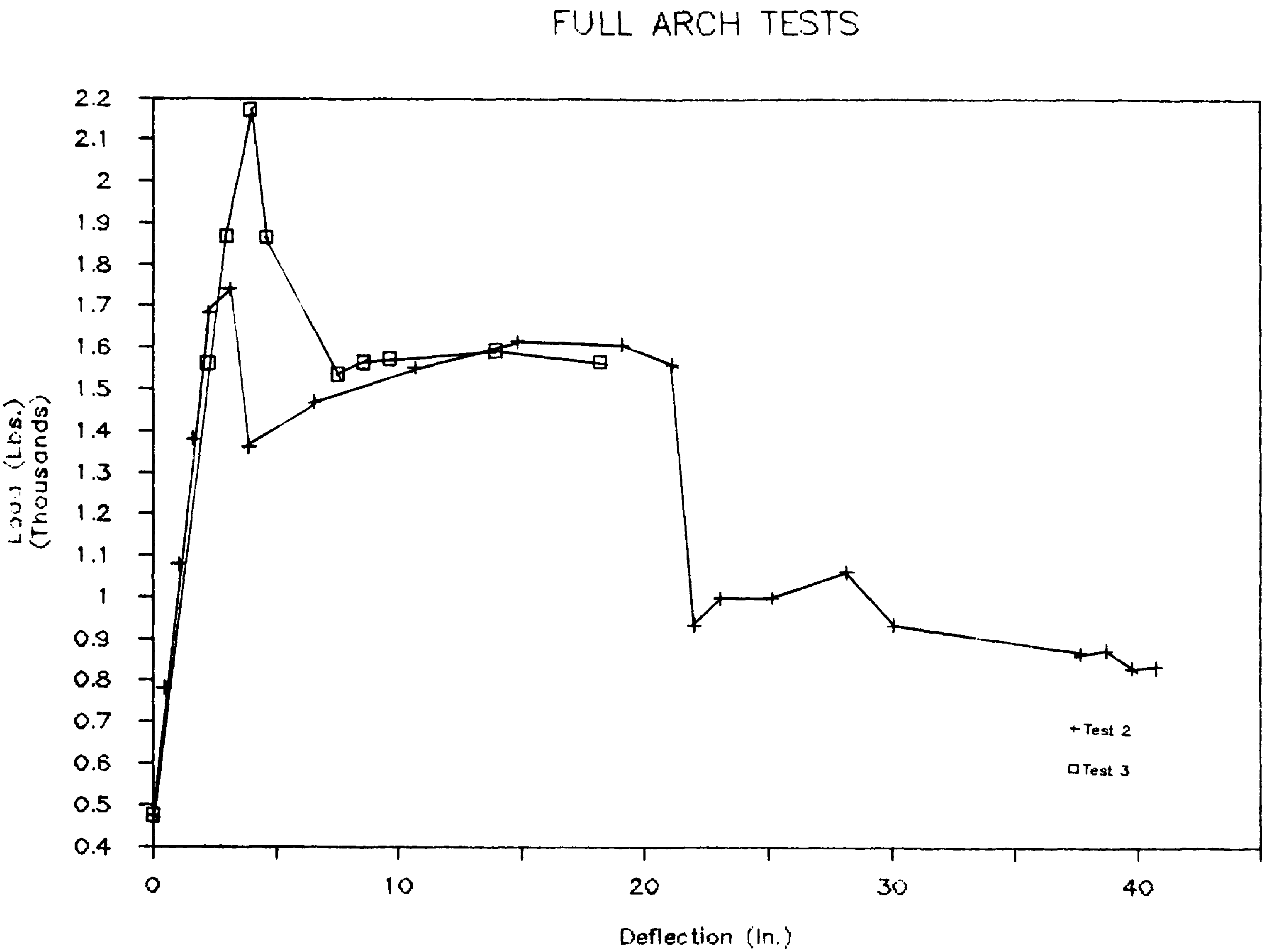

Figure 25. Load-deflection curves for full arch tests 2 and 3.

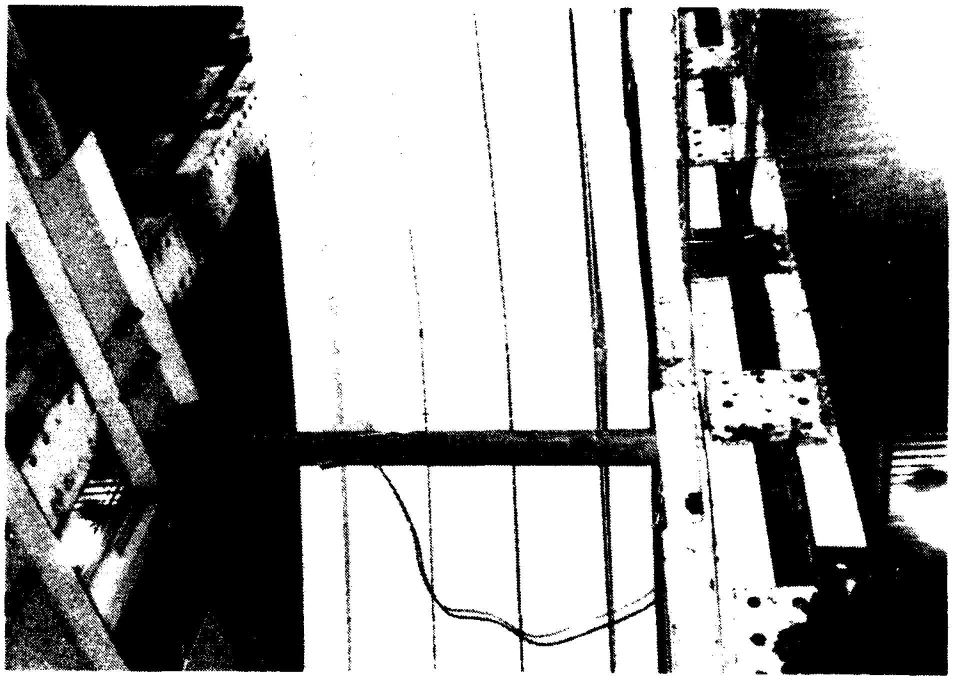

Figure 26. Quarterpoint buckling of the full arch in negative moment.

Summary of Test Results. The critical moments obtained from the cantilever beam tests correspond to the moments that would cause local buckling at the fixed base of the real arch structure. The following values were obtained: a critical positive moment of 3000 in.-lb/in. with an upper bound of 3400 in.-lb/in., and a critical negative moment of 2400 in.-lb/in. with an upper bound of 2600 in.-lb/in.

For the straight, simply supported beam, the full-scale tests indicated a critical positive moment of 2600 in.-lb/in. The full-scale tests on all other cases of the simply supported beam failed to provide reasonable results for a variety of technical reasons. In fact, the results were all higher than obtained in the cantilever beam tests. It is clear from the results that the boundary conditions and load application artificially stiffened the panel sections. Also, the short length of the specimens probably contributed to their stiffness.

The critical positive moments obtained in the full-scale tests of the arch were found to vary between individual tests. This result may reflect the effect of the initial imperfections present in the shell. Because the degree and pattern of potential initial imperfections in a real structure cannot be predicted, the minimum positive moment corresponding to the formation of the first hinge of 1200 in.-lb/in. (Figure 3) can be considered an approximate lower bound for the critical positive moment away from the fixed base.

Since buckling under negative moment was restricted to a rather small region, the results obtained for the cantilever beam can also be used to approximate the critical negative moment away from the fixed end. From observations, local buckling under negative moment in the case of the cantilever beam occurred well within a distance of 10 in. from the fixed end. The corresponding critical negative moment away from the fixed end can be estimated by multiplying the moment at the fixed end by 0.85. This factor corresponds to the moment at 8 in. from the base. Accordingly, the critical negative moment of the curved beam away from the fixed base was estimated (conservatively) to be 2000 in.-lb/in., based on the corresponding lower bound of the cantilever tests.

The critical negative moment developed in the full arch tests was estimated to be in the range of 1300 to 2000 in.-lb/in. The critical stress at the extreme fibers (seam) in the region where the second hinge was formed was found to be, on the average, 35 ksi. By taking into account the effect of the minor corrugations on the stress distribution within the curved panel, the corresponding critical negative moment is estimated to be 1700 in.-lb/in.[12] This moment is close to the 2000 in.-lb/in. moment estimated from the cantilever beam tests results. Based on similar results obtained in the cantilever beam tests, the critical negative moment determined numerically is considered to be a good approximation, adequate for estimating the range of the critical negative moment.

To summarize the test results, the following critical moments were determined:

- Fixed base: the positive moment is bounded by 3000 and 3400 in.-lb/in. and the negative moment by 2400 and 2600 in.-lb/in.

- Away from fixed base: the positive moment is bounded by 1200 and 1700 in.-lb/in. and the negative moment by 1700 and 2000 in.-lb/in.

Formation of Collapse Mechanisms

The development of collapse mechanisms is considered the most probable mode of failure in the type of structures under investigation. In particular, collapse mechanism development through the formation of hinges was analyzed using the critical moment bounds determined in full-scale testing of sections of the intermediate building.

The behavior of the barrel-type shells depends very much on their aspect ratio (length/radius).[13] In this study, only long shells were considered, for which the effect of the shells' end walls can be ignored.[14] This assumption (long shell) makes it possible to use simpler models for numerical nonlinear analysis.

Two building sizes were analyzed. One was a large building, 72 ft high by 26 ft span, constructed using material having a thickness of 0.035 in. This building, as one of the largest specified by the machine manufacturer[15] was selected to determine the limiting buckling behavior for this type of structure. The second structure was an intermediate-size building (50 ft by 18 ft) made with material of the same thickness. It is considered a representative size for these structures.

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[12] D. Briassoulis, et al.

[13] D. P. Billington, *Thin Shell Concrete Structures*, 2nd ed. (McGraw-Hill, 1982).

[14] M. N. El-Atrouzy and G. Abdel-Sayed, "Prebuckling Analysis of Orthotropic Barrel-Shells," *American Society of Civil Engineers, Proceedings, Journal of Structural Division*, Vol 104, ST11 (1978), pp 1775-1786.

[15] *K-Span, Metal Building Data Manual.*

The structure was analyzed under a line load with the same orthotropic model used in the numerical analysis.[16] Figure 27 presents the numerical analysis results (note that this nonlinear analysis does not account for localized nonlinearities; local buckling was determined from test results). When the critical positive moment was reached, a hinge formed at mid-span at the loading levels shown in Figure 27. When this hinge formed, a moment redistribution occurred within the structure. For the arch with a fixed base and a hinge introduced at the top, numerical analysis (using the orthotropic model) yielded the second curve of Figure 27. The structure was much softer now, and a second hinge was expected to form under the critical negative moment. The critical negative moment was reached at the quarterpoint of the arch at nearly half the loading level at which the first hinge formed. Therefore, assuming that the load remains constant, formation of the first hinge means total collapse of the structure, causing simultaneous formation of hinges at the quarterpoints.

Loading

In addition to the dead load of the shell, which is 3 lb/sq ft snow and wind loading were the conditions considered. The snow and wind loading distribution on barrel shells given by the different codes was similar but not the same. The American National Standards Institute (ANSI) standards[17] were used for all loading conditions. A basic wind velocity of 90 mph was used as the reference wind loading along with a ground snow reference load of 100 lb/sq ft Two cases of snow loading were considered: snow not combined with wind (balanced or symmetric) and snow combined with wind (unbalanced or asymmetric). Details about the loading pressures are discussed in USACERL TR M-88/01.

Ultimate Load Bounds

To determine the bounds of the ultimate loads, the following method was used. All critical loads were determined for the extreme values of the moment distribution due to the loading under consideration. The minimum of these loads defined the load at which the first hinge was expected to form. If other critical loads were close to the governing one, simultaneous formation of all these hinges was expected due to the moment redistribution that followed the formation of the first hinge. Thus, the governing critical load also defined the ultimate load of the structure under the considered loading. It was shown that, with all loading conditions considered, collapse mechanisms develop as a result of simultaneous formation of several hinges (Figure 28). In particular, the following bounds to the ultimate loads were obtained. For the balanced snow loading, it was shown that the lower bound to the ultimate snow load corresponds to:

$$p_{cr} > 80 \text{ to } 100 \text{ lb/sq ft ground load (intermediate building)}$$

$$p_{cr} > 1.5 \text{ to } 1.9 \ 30 \text{ to } 40 \text{ lb/sq ft ground load (large building)}$$

This corresponds to a simultaneous formation of hinges at the base and the quarterpoints, and to instantaneous collapse of the structure.

In addition, taking the maximum upper limit for the formation of the first hinge, it can be said that the critical balanced snow load can be no larger than:

$$p_{cr} < 125 \text{ lb/sq ft ground load (intermediate building)}$$

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[16] D. Briassoulis, et al.

[17] American National Standards Institute (ANSI) Standard A58.1, *Minimum Design Loads for Buildings and Other Structures* (ANSI, 1982).

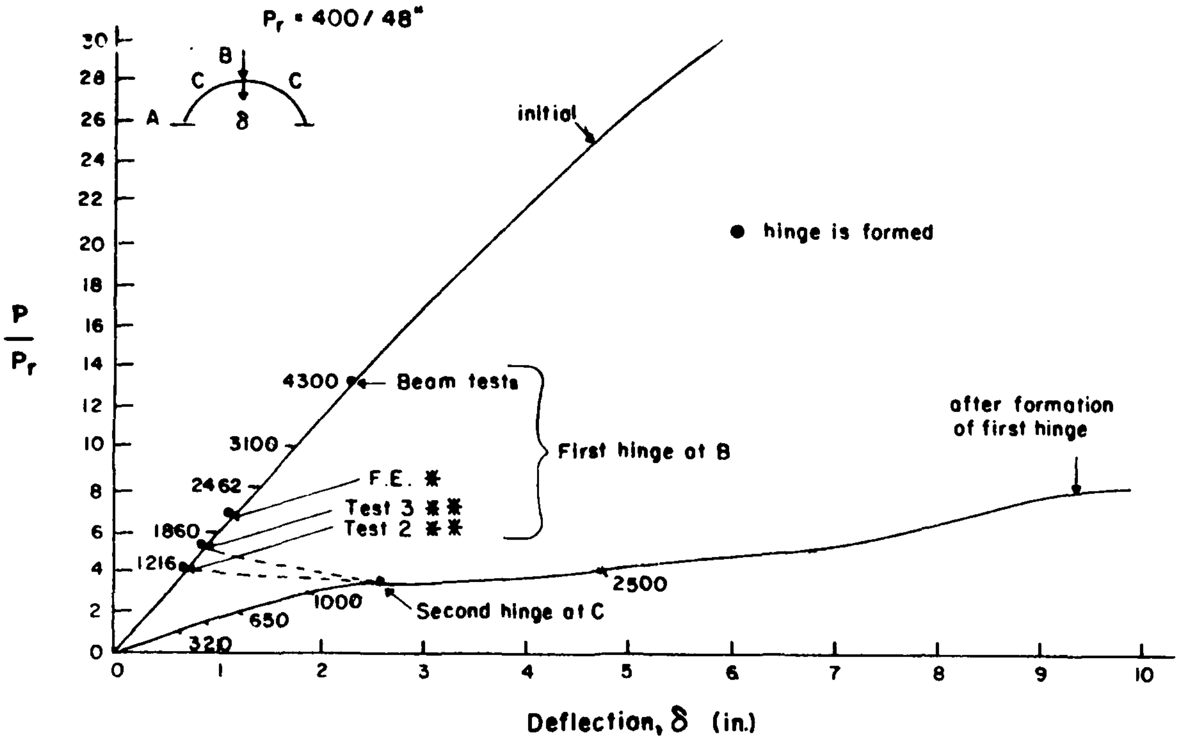

Figure 27. **Numerical analysis of the intermediate structure under a line load and critical moments obtained from full-scale tests.**

$$p_{cr} < 50 \text{ lb/sq ft ground load (large building)}$$

The ultimate balanced snow load can then be assumed to be 80 lb/sq ft and 30 lb/sq ft, conservatively, for the intermediate and large buildings, respectively (ground snow load).

Overall buckling of the large arch structure when hinges have already formed at the base was determined in the numerical analysis to occur at 73 lb/sq ft. This is still outside the limits corresponding to the formation of collapse mechanisms. Therefore, overall buckling could become a design consideration only for very large buildings.

For the unbalanced snow loading, the lower bound of the ultimate load was found to be:

$$p_{cr} > 35 \text{ to } 51 \text{ lb/sq ft ground load (intermediate building)}$$

$$p_{cr} > 14 \text{ to } 21 \text{ lb/sq ft ground load (large building)}$$

where the lower limits of these ranges correspond to the formation of hinges at the region of maximum positive moment away from the base. These lower values account for initial imperfections and are considered conservative.

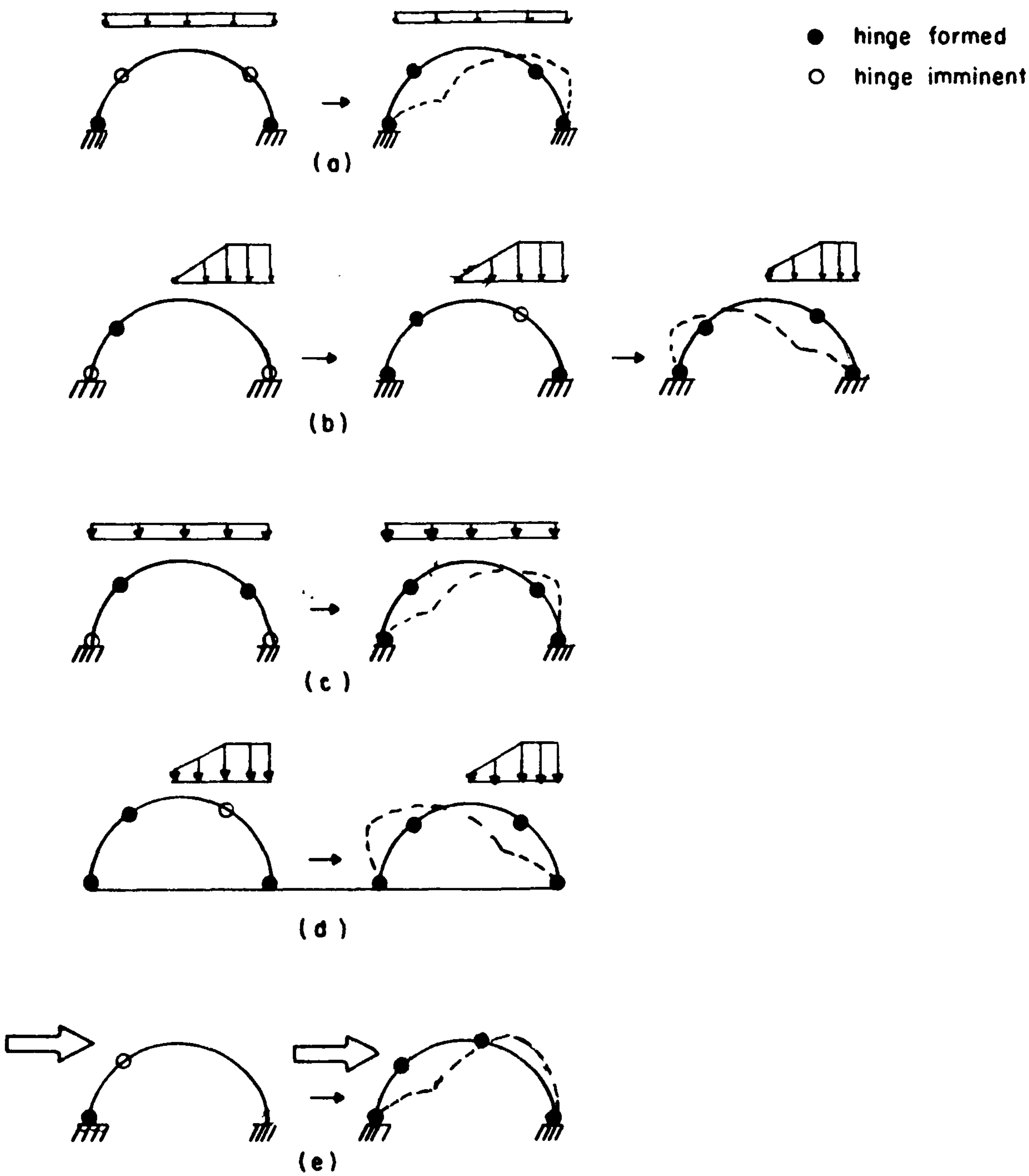

Figure 28. Collapse mechanisms for the intermediate (a and b) and large (c through e) structures under balanced (a,c), unbalanced (b,d), and wind loading (e).

The ultimate unbalanced snow load is not expected to exceed the maximum critical loads corresponding to the formation of the first hinge, which are:

$$p_{cr} < 83 \text{ lb/sq ft ground load (intermediate building)}$$

$$p_{cr} < 33 \text{ lb/sq ft unbalanced snow load (ground load)}$$

The design unbalanced snow load (ground load) can then be estimated to be 35 lb/sq ft and 14 lb/sq ft for the intermediate and large buildings, respectively. This estimate is conservative.

Under wind loading, the first hinge(s) is expected to form in the region of the base at the windward side (Figure 28c). Collapse of the structure, however, is not possible unless a second hinge forms. Therefore, the lower bound of the ultimate wind load is defined within a range corresponding to the formation of the first and second hinges, which is:

$$V_{cr} > 104 \text{ to } 107 \text{ mph wind velocity (intermediate building)}$$

$$V_{cr} > 71 \text{ to } 74 \text{ mph wind velocity (large building)}$$

In addition, the critical wind load (velocity) cannot exceed the upper bound for the formation of the first hinge:

$$V_{cr} < 127 \text{ mph wind velocity (intermediate building)}$$

$$V_{cr} < 87 \text{ mph wind velocity (large building)}$$

Collapse of the structure is imminent after the formation of the first hinge.

Material Durability

A material exposure test was conducted to determine the performance of the material in adverse climates. Of particular concern was the inevitable scraping of the material during forming and the effect of roll-forming on the galvanized and painted surfaces. Aluminum panels were also tested as an alternative construction material.

Test Method

The following ASTM test methods were used for testing and evaluating the materials:[18]

D 610-68 Evaluating Degree of Rusting on Painted Steel Surfaces

D 1014-66 Conducting Material Exposure Tests of Paints on Steel

D 1654-79a Painted or Coated Specimens Subjected to a Corrosive Environment

[18] *ASTM Annual Book of Standards.*

Test Site

The testing was conducted at the U.S. Army Tropic Test Center, Panama. The Center is equipped with facilities to maintain the test specimens and offers environmental conditions to testing accelerated weathering of the materials. Two sites were used: the coastal and open areas. Both sites are subject to considerable seawater fallout or condensation, with the coastal site being the more severe location.

Sample Preparation

Each sample consisted of two channels seamed together to form approximate overall dimensions of 24 in. wide by 24 in. long by 6 in. deep. The cut edges of each panel were coated to protect the exposed metal. Each sample was scribed in accordance with ASTM test method D 1654. Scratches in the paint as a result of forming or handling were left unrepaired. The samples were then exposed in accordance with ASTM D 1040, except that the inclination was 30 degrees.

Three combinations of materials were formed in both the straight (end wall) and curved configurations. One of each combination and configuration was exposed at each site, except for the one straight steel panel coated with polyester paint, which was exposed at the coastal site. The panels were exposed from October 1985 to July 1988.

Test Results

The polyester coating cracked when the panels were formed. Some of the cracks were visible to the naked eye. On an open inland exposure, the cracks blistered along the bends. In addition, blisters formed along the score lines, which results from the formation of zinc salts where the galvanizing was exposed to moisture and salts. No rust was seen, so the galvanizing did protect the steel from rusting.

The coastal exposure of the polyester coating resulted in a greater degree of blistering along the bends and score lines. Blisters formed on the open flat panel area and are also larger than those formed on an open inland exposure. Some pinpoint rusting occurred along the exposed joint bends. In each case, only a small percentage of the total area was rusted, but the rust was concentrated at the joint bends.

The polyester coating chalked visibly in the sunlight exposure at both locations, which indicates the binder was degraded by ultraviolet light. The degradation eventually leads to loss of the coating and exposure of the substrate.

The Kynar system did not chalk significantly in the sunlight. But, the Kynar system also cracked along the bends during the forming operation. On the open inland panels, the cracks formed blisters along the bends. No rust formed on the open inland exposed panels.

The Kynar panels in coastal exposure suffered a greater degree of blistering along the bends and score lines. White zinc oxides formed along the bends and score lines. Rusting was concentrated along the exposed joint bends.

Overall, the Kynar coating system performed better than the polyester system. Though blistering, rusting, and cracking were similar, the Kynar system was more resistant to the degradative effects of sunlight exposure. The performance of either system in a marine environment will be greatly enhanced by applying a topcoat after forming the steel. The topcoat seals or bridges the cracks from the forming

operation and extends the effective life of the coating system. The coating manufacturer can recommend a top coat.

The uncoated aluminum panels were exposed a the coastal location and were moderately pitted after 33 months. Therefore, the expected useful life of unpainted aluminum structures in a coastal environment would be limited to a few years. The lifetime would be extended if the structures were washed with fresh water at regular intervals to rinse away soluble salts. The aluminum should be painted after forming. A suitable paint system for the exterior aluminum surfaces would be a high-performance vinyl such as Steel Structures Painting Council Specification Paint 9. It is self-priming and must be spray-applied to achieve a minimum dry film thickness of 5.0 mils. Interior surfaces should also be painted if pitting occurs. A suitable interior coating system would be the same vinyl system or an alkyd enamel coating system, which could be applied by spray or brush.

5 CONCLUSIONS AND RECOMMENDATIONS

USACERL has investigated the K-Span building system for potential use as a RELMS in the event of full-scale military mobilization. This report has presented the findings on constructibility, availability, logistics, cost, structural integrity and material durability.

The results suggest that the K-Span building system has many beneficial characteristics for mobilization construction. Field tests showed that it is erected easily and quickly. Skills involved, with the exception of crane operation and welding, are simple and repetitive. Since most of the structural components are fabricated onsite, the system is both low volume and lightweight. The specialized roll-forming machine and accessories are trailer-mounted and transportable. Costs are very competitive with conventional construction techniques.

Structural integrity of the system is sound, which would enable construction of medium- to large-span structures in environments that have moderate to severe snow and wind load conditions. Load capacities are even higher in short structures for which end wall effects can be considered.

Disadvantages of the system include the need for specialized equipment for construction. Besides the forming machine, a crane or high-mast forklift is required to lift the arches into place. It is best to have a manlift or cherry picker for end wall construction, and a welder and cutting torch are required. Earth working equipment may also be required, depending on site conditions and foundation design.

Material tests showed that prepainted coating on the sheet steel is cracked during forming. This can result in corrosion of the steel or aluminum, especially in a coastal environment. If long term use is desired or if conditions are corrosive, a top coat is recommended for the prepainted steel, and paint is recommended for the aluminum.

Based on the projected availability, K-Span could provide a small portion of early mobilization requirements. With 28 machines currently available, a maximum of 420,000 sq ft/day of bare structure could conceivably be completed with short lead time. However, to take full advantage of the system's rapid erectability, approximately 2 weeks' worth of materials would have to be stockpiled. This timeframe corresponds with the lead time required by the steel industry to increase the production rate of galvanized sheet steel. After 2 weeks, the steel industry's capacity to produce galvanized sheet steel would far exceed the capacity of the available K-Span equipment.

METRIC CONVERSION FACTORS

1 in.	=	25.4 mm
1 ft	=	0.305 m
1 lb	=	0.453 kg
1 ton	=	0.9078 t
1 cu ft	=	0.028 m^3
1 mi	=	1.61 km
1 sq ft	=	0.093 m^2
1 cu yd	=	0.7646 m^3

APPENDIX:

LOAD TEST RESULTS

Cantilever Positive Moment - Test 1

Load	Strain Gauge Measurements (in/in)								Deflections (in)	
(lbs)	1	2	3	4	5	6	7	8	d1	d2
0	-0.00000	0.000011	0.000000	0.000001	0.000016	0.000006	0.000000	-0.00001	0	0
361.71	0.000031	0.000053	0.000058	0.000094	0.000331	0.000148	-0.00005	-0.00026	0.002446	0.152621
723.41	0.000062	0.000094	0.000115	0.000190	0.000649	0.000286	-0.00011	-0.00054	0.011594	0.324991
1083.57	0.000095	0.000135	0.000175	0.000296	0.000969	0.000425	-0.00019	-0.00084	0.02263	0.502071
1444.97	0.000129	0.000175	0.000235	0.000419	0.001302	0.000566	-0.00027	-0.00116	0.033262	0.703451
1806.27	0.000172	0.000234	0.0003	0.000561	0.001633	0.000717	-0.00035	-0.00149	0.042244	0.917081
2166.77	0.000216	0.000262	0.000360	0.000749	0.001977	0.000882	-0.00045	-0.00184	0.058105	1.165071
2526.77	0.000259	0.000300	0.000427	0.000928	0.002383	0.001079	-0.00057	-0.00225	0.072783	1.422971
2647.37	0.000269	0.000308	0.000453	0.001014	0.002547	0.001160	-0.00061	-0.00241	0.078081	1.512771
2767.77	0.000270	0.000315	0.000481	0.001091	0.002728	0.001252	-0.00065	-0.00258	0.084145	1.617671
2887.77	0.000259	0.000318	0.000511	0.001182	0.00293	0.001353	-0.00070	-0.00278	0.089871	1.727171
3007.77	0.000245	0.010693	0.000553	0.001266	0.003195	0.001474	-0.00083	-0.00312	0.095335	1.876471

Cantilever Positive Moment - Test 2

Load	Strain Gauge Measurements (in/in)										Deflections (in)	
(lbs)	1	2	3	4	5	6	7	8	9	10	d1	d2
0.0	-0.00000	0.000007	0.000000	0.000001	-0.00000	0	0.000003	0.000003	0.000001	0.000006	0	0
361.4	-0.00003	0.000011	0.000189	-0.00003	0.000357	0.000056	-0.00005	-0.00020	-0.00014	-0.00029	0.003623	0.173923
723.3	-0.00005	0.000025	0.000385	-0.00006	0.000720	0.000114	-0.00012	-0.00041	-0.00028	-0.00057	0.014083	0.364133
1084.6	-0.00008	0.000035	0.000582	-0.00009	0.001066	0.000164	-0.00018	-0.00063	-0.00041	-0.00093	0.024635	0.549243
1445.9	-0.00010	0.000052	0.000793	-0.00012	0.001410	0.000219	-0.00025	-0.00085	-0.00054	-0.00132	0.036229	0.743463
1807.4	-0.00012	0.000069	0.001013	-0.00149	0.001774	0.000277	-0.00032	-0.00109	-0.00067	0.97579	0.051514	0.971513
2048.1	-0.00014	0.000074	0.001164	-0.00017	0.002039	0.000318	-0.00037	-0.00128	-0.00075	0.97577	0.062299	1.135553
2409.5	-0.00017	0.000069	0.001434	-0.00022	0.002534	0.000393	-0.00045	-0.00159	-0.00086	0.97577	0.079834	1.401653
2651.5	0.96836	0.000053	0.001668	-0.00026	0.003012	0.000455	-0.00051	-0.00183	-0.00096	0.97575	0.092716	1.604353
2771.7	0.96836	0.000043	0.001809	-0.00028	0.003271	0.000493	-0.00054	-0.00196	-0.00101	0.97573	0.099875	1.711753
2562.1	0.96836	0.000002	0.002159	0.97005	0.002038	0.000213	0.000124	-0.00242	-0.00099	0.97573	0.093400	2.715853

Cantilever Positive Moment - Test 3

Load	Strain Gauge Measurements (in/in)										Deflections (in)	
(lbs)	1	2	3	4	5	6	7	8	9	10	d1	d2
0.0	-0.00002	-0.00004	-0.00002	-0.00009	-0.00001	0.000039	0.000024	0.000092	0.000088	0.000166	0	0
361.5	0.000009	0.000026	0.000015	0.000053	0.000009	-0.00001	0.000001	-0.00004	-0.00004	-0.00006	0.009849	0.20711
722.3	0.000043	0.000091	0.000051	0.000189	0.000034	-0.00007	-0.00000	-0.00019	-0.00016	-0.00030	0.022863	0.41282
1084.0	0.000080	0.000161	0.000089	0.000331	0.000065	-0.00012	0.000000	-0.00034	-0.00029	-0.00054	0.038093	0.6349
1445.3	0.000116	0.000231	0.000125	0.000477	0.000095	-0.00018	0.000001	-0.00049	-0.00043	-0.00081	0.054352	0.85571
1806.5	0.000155	0.000303	0.000164	0.000637	0.000126	-0.00023	0.000001	-0.00064	-0.00058	-0.00109	0.069913	1.08006
2167.0	0.0002	0.000378	0.000208	0.000800	0.000151	-0.00029	0.000009	-0.00079	-0.00072	-0.00139	0.086222	1.31899
2530.2	0.000240	0.000434	0.000251	0.000961	0.000152	-0.00034	0.00004	-0.00094	-0.00089	-0.00178	0.105333	1.56919
2892.0	0.000252	0.000480	0.000312	0.001171	0.000173	-0.00041	0.000084	-0.00111	-0.00108	-0.00222	0.123903	1.84859
3253.9	0.000234	0.000499	0.000372	0.001431	0.000236	-0.00053	0.000116	-0.00134	-0.00129	-0.00296	0.141683	2.16299
3374.8	0.000232	0.000506	0.000395	0.001537	0.000278	-0.00058	0.000129	-0.00145	-0.00136	-0.0034	0.147613	2.27949
2034.2	0.000198	0.000330	0.000109	-0.00013	0.000341	0.001258	0.001915	-0.00150	-0.00127	-0.00804	0.118313	3.88249

Cantilever Negative Moment - Test 1

Load	Strain Gauge Measurements (in/in)								Deflection (in)	
(lbs)	1	2	3	4	5	6	7	8	d1	d2
0	-0.00000	-0.00000	-0.00000	-0.00000	-0.00003	-0.00000	0.000001	0.000000	0	0
239.959	0.000063	0.000064	0.000058	-0.00002	-0.00008	0.000027	-0.00000	0.000116	-0.00044	0.097858
600.799	0.00017	0.000173	0.000156	-0.00004	-0.00017	0.000073	-0.00001	0.000288	0.007823	0.273218
841.769	0.000243	0.000250	0.000225	-0.00005	-0.00021	0.000106	-0.00002	0.000404	0.016063	0.405748
1082.119	0.000316	0.000328	0.000296	-0.00006	-0.00021	0.000140	-0.00002	0.000516	0.024506	0.533578
1322.419	0.000399	0.000412	0.000375	-0.00009	-0.00026	0.000181	-0.00003	0.000625	0.034303	0.675348
1683.319	0.000531	0.000554	0.000510	-0.00013		0.000244	-0.00002	0.000775	0.053022	0.922828
1923.319	0.000631	0.000660	0.000612	-0.00016		0.000288	-0.00002	0.000866	0.069208	1.114728
2163.819	0.000743	0.000784	0.000731	-0.00014		0.000329	-0.00000	0.000964	0.086112	1.317428
2403.919	0.000876	0.000932	0.000873	-0.00008		0.000362	0.000006	0.001076	0.105191	1.554628
2524.319	0.000956	0.001017	0.000951	-0.00003		0.000382	0.000010	0.001133	0.113391	1.662828
2644.819	0.001050	0.001115	0.001044	0.000015		0.000399	0.000013	0.001190	0.130241	1.855228

Cantilever Negative Moment - Test 2

Load	Strain Gauge Measurements (in/in)								Deflection (in)	
(lbs)	1	2	3	4	5	6	7	8	d1	d2
0	-0.00002	-0.00001	-0.00002	-0.00000	0.014803	-0.00000	0.000002	-0.00003	0	0
240.507	0.000028	0.000024	0.000037	0.060001	0.003238	0.000005	0.000000	0.000049	-0.00032	0.151287
505.347	0.000092	0.000076	0.000116	0.000013	-0.00069	0.000020	0.000002	0.000148	0.012703	0.3505
759.977	0.000151	0.000126	0.000191	0.000025	-0.00685	0.000034	0.000009	0.000238	0.027399	0.54116
1068.507	0.000221	0.000184	0.000279	0.000052	-0.00313	0.000052	0.000016	0.000338	0.046976	0.77109
1441.007	0.000306	0.000252	0.000386	0.000080	-0.00113	0.000073	0.000024	0.000449	0.070821	1.04389
2044.107	0.00048	0.000402	0.000629	0.000150	-0.00071	0.000123	0.000040	0.000625	0.116869	1.59391
2284.907	0.000558	0.000476	0.000767	0.000161	-0.00055	0.000152	0.000046	0.000712	0.131799	1.80001
2404.907	0.000612	0.000565	0.001037	0.96924	0.56061	0.000178	0.000068	0.000845	0.138929	1.92871
2177.807	0.96905	-0.00032	0.96826	0.96922	0.8442	-0.00087	-0.00019	0.000753	0.142349	2.57991

Cantilever Negative Moment - Test 3

Load	Strain Gauge Measurements (in/in)								Deflection (in)	
(lbs)	1	2	3	4	5	6	7	8	d1	d2
0	-0.00000	0.000000	-0.00000	0.000000	0.000005	-0.00000	0	-0.00000	0	0
240.537	0.000014	0.000008	0.000015	0.000020	-0.00027	-0.00004	0.000010	0.000133	-0.00071	0.118667
600.857	0.000043	0.000027	0.000053	0.000064	-0.00069	-0.00009	0.000028	0.000344	0.001287	0.323697
841.757	0.000067	0.000044	0.000082	0.000099	-0.00098	-0.00013	0.000040	0.000493	0.009742	0.468817
1202.027	0.000104	0.000070	0.000127	0.000158	-0.00143	-0.00019	0.000056	0.000726	0.022606	0.692037
1442.427	0.000132	0.000091	0.000160	0.000205	-0.00174	-0.00023	0.000069	0.000884	0.032274	0.849727
1683.027	0.000159	0.000110	0.000194	0.000254	-0.00207	-0.00028	0.000077	0.001085	0.043813	1.015487
1923.327	0.000191	0.000135	0.000230	0.000312	-0.00242	-0.00032	0.000088	0.001239	0.058301	1.202087
2164.327	0.000227	0.000164	0.000264	0.000386	-0.00283	-0.00037	0.000100	0.001398	0.071183	1.390187
2284.427	0.000246	0.000179	0.000281	0.000436	-0.00308	-0.00041	0.000105	0.001483	0.077621	1.470687
2405.027	0.000266	0.000195	0.000295	0.000506	-0.00335	-0.00045	0.000105	0.001578	0.084727	1.572787
2524.927	0.000303	0.000225	0.000317	0.000649	-0.00386	-0.00052	0.000121	0.001757	0.092998	1.669307

Straight Single Panel Positive Moment - Test 1

Load (lbs)	Strain Gauge Measurments (in/in) 1	2	3	4	5	6	7	8	9	10	Deflection (in)
0	0.000003	0.000001	0.000000	-0.00000	-0.00000	0	0.000000	0.000000	0.000001	0.000001	0.0000
262	0.000043	0.000042	0.000025	-0.00002	-0.00007	-0.00006	-0.00002	0.000031	0.000043	0.000040	0.0220
514	0.000079	0.000079	0.000052	-0.00005	-0.00016	-0.00013	-0.00004	0.00006	0.000092	0.000079	0.0458
764	0.000116	0.000113	0.000079	-0.00009	-0.00024	-0.00019	-0.00007	0.000085	0.000135	0.000117	0.0668
1062	0.000160	0.000155	0.000113	-0.00012	-0.00035	-0.00028	-0.00010	0.000116	0.000186	0.000164	0.0924
1263	0.000192	0.000184	0.000139	-0.00015	-0.00043	-0.00034	-0.00013	0.000134	0.000219	0.000197	0.1127
1513	0.000237	0.000220	0.000170	-0.00020	-0.00055	-0.00042	-0.00017	0.000156	0.000257	0.000240	0.1405
1765	0.000284	0.00026	0.000208	-0.00025	-0.00067	-0.00051	-0.00021	0.000177	0.000296	0.000285	0.1695
2015	0.000339	0.000307	0.000236	-0.00029	-0.00082	-0.00062	-0.00026	0.000191	0.000337	0.000339	0.2062
1733	0.000468	0.000266	-0.00020	0.000469	-0.00095	-0.00196	-0.00104	-0.00036	0.000451	0.000515	0.3660
1757	0.000508	0.000229	-0.00034	0.000701	-0.00096	-0.00258	-0.00116	-0.00053	0.000459	0.000572	0.5493

Straight Single Panel Positive Moment - Test 2

Load (lbs)	Strain Gauge measurements (in/in) 1	2	3	4	5	6	7	8	9	10	Deflection (in)
0	-0.00000	-0.00000	-0.00000	0.000001	-0.00000	0.000025	0.000002	0.000000	0	-0.00000	0.0000
101	0.000013	0.000014	0.000008	-0.00001	-0.00003	-0.00000	-0.00000	0.000012	0.000016	0.000018	0.0119
203	0.000022	0.000026	0.000016	-0.00002	-0.00006	-0.00001	-0.00001	0.000021	0.000031	0.000037	0.0192
304	0.000035	0.000038	0.000025	-0.00003	-0.00010	-0.00004	-0.00002	0.000031	0.000046	0.000056	0.0271
404	0.000048	0.000052	0.000035	-0.00004	-0.00013	-0.00006	-0.00003	0.000040	0.000061	0.000075	0.0357
606	0.000074	0.000081	0.000057	-0.00007	-0.00020	-0.00011	-0.00005	0.000060	0.000093	0.000115	0.0554
807	0.000102	0.000112	0.000078	-0.00010	-0.00027	-0.00016	-0.00007	0.000081	0.000125	0.000154	0.0735
1106	0.000140	0.000156	0.000108	-0.00014	-0.00039	-0.00025	-0.00010	0.000110	0.000174	0.000209	0.1035
1809	0.000231	0.000271	0.000177	-0.00027	-0.00068	-0.00050	-0.00022	0.000169	0.000296	0.000339	0.1797
2009	0.000259	0.000309	0.000197	-0.00030	-0.00078	-0.00061	-0.00028	0.000184	0.000336	0.000380	0.2053
2311	0.000305	0.000378	0.000191	0.000012	-0.00090	-0.00118	-0.00063	0.000139	0.000398	0.000438	0.2566
2512	0.000334	0.000426	0.000196	0.000278	-0.00101	-0.00123	-0.00060	0.000109	0.000448	0.000481	0.2986

Curved Single Panel Positive Moment - Test 1

Load (lbs)	Strain Gauge Measurments (in/in) 1	2	3	4	5	6	7	8	9	10	Deflection (in)
0	-0.00000	0.000000	-0.00000	0.000000	0.000002	0.000002	0.000000	0.000000	0.000000	0.000001	0.0000
301	0.000027	0.000016	-0.00002	0.000005	-0.00006	-0.00008	-0.00000	-0.00003	0.000036	0.000013	0.0517
605	0.000058	0.000025	-0.00007	0.000012	-0.00013	-0.00016	0.000000	-0.00007	0.000072	0.000030	0.0924
909	0.000088	0.000027	-0.00011	0.000020	-0.00019	-0.00024	0.000004	-0.00011	0.000108	0.000047	0.1282
1211	0.000117	0.000027	-0.00014	0.000029	-0.00026	-0.00033	0.000005	-0.00014	0.000145	0.000063	0.1677
1514	0.000148	0.000039	-0.00017	0.000035	-0.00033	-0.00042	0.000005	-0.00018	0.000182	0.000079	0.2113
1817	0.000178	0.000052	-0.00020	0.000039	-0.00041	-0.00051	0.000003	-0.00021	0.000219	0.000094	0.2526
2118	0.000204	0.000068	-0.00023	0.000046	-0.00049	-0.00060	0.000002	-0.00024	0.000256	0.000109	0.2976
2419	0.000232	0.000083	-0.00025	0.000054	-0.00057	-0.00069	0.000002	-0.00027	0.000297	0.000126	0.3409
2722	0.000258	0.0001	-0.00027	0.000061	-0.00066	-0.00078	0.000002	-0.00029	0.000340	0.000144	0.3854
3024	0.000281	0.000117	-0.00030	0.000070	-0.00075	-0.00087	0.000000	-0.00032	0.000383	0.000161	0.4302
3627	0.000330	0.000165	-0.00036	0.000088	-0.00097	-0.00105	0.000000	-0.00037	0.000473	0.000207	0.5246
3931	0.000351	0.000196	-0.00040	0.000096	-0.00111	-0.00113	-0.00000	-0.00040	0.000521	0.000235	0.5787
4231	0.000375	0.000234	-0.00046	0.000103	-0.00130	-0.00121	0.000001	-0.00044	0.000583	0.000261	0.6463
4533	0.000397	0.000278	-0.00055	0.000107	-0.00157	-0.00128	0.000003	-0.00048	0.000665	0.000289	0.7332
4835	0.000411	0.000323	-0.00069	0.000090	-0.00196	-0.00137	0.000007	-0.00054	0.000771	0.000319	0.8525
4935	0.000409	0.00034	-0.00078	0.000062	-0.00219	-0.00143	0.000011	-0.00058	0.000826	0.000336	0.9322
4974	0.000400	0.000352	-0.00090	-0.00002	-0.00251	-0.00158	0.000063	-0.00063	0.000905	0.000360	1.0669
1845	0.000420	0.000202	-0.00029	-0.00105	-0.00170	-0.00065	0.000602	0.001635	0.000745	0.000361	4.0282

Curved Single Panel Positive Moment - Test 2

Load (lbs)	Strain Gauge Measurments (in/in) 1	2	3	4	5	6	7	8	9	10	Deflection (in)
0	0.000000	-0.00000	0.000002	0.000002	-0.00000	0	0.000000	0.000003	-0.00000	0.000000	0.0000
303	0.000008	0.000003	0.000051	0.000006	-0.00006	-0.00008	0.000004	0.000072	0.000034	0.000032	0.1165
605	0.000018	0.000008	0.000100	0.000014	-0.00013	-0.00016	0.000010	0.000144	0.000070	0.000161	0.2626
905	0.000026	0.000011	0.000163	0.000022	-0.00021	-0.00025	0.000016	0.000235	0.000106	0.000237	0.4400
1204	0.000033	0.000016	0.000256	0.000029	-0.00029	-0.00034	0.000024	0.00034	0.000139	0.000299	0.5904
1505	0.000043	0.000021	0.000320	0.000040	-0.00037		0.000033	0.000430	0.000177	0.000372	0.7094
1805	0.000050	0.000029	0.000415	0.000060	-0.00044	-0.00042	0.000046	0.000581	0.000220	0.00045	0.8108
2106	0.000053	0.000045	0.000633	0.000087	-0.00052	-0.00057	0.000059	0.000765	0.000262	0.000524	0.9023
2406	0.000056	0.000077	0.001048	0.000118	-0.00061	-0.00069	0.000086	0.001078	0.000303	0.000591	1.0187
2708	0.000058	0.000097	0.001202	0.000136	-0.00069	-0.00082	0.000094	0.001115	0.000328	0.000662	1.0783
3009	0.000062	0.000117	0.001418	0.000159	-0.00082	-0.00088	0.000108	0.001286	0.000363	0.000633	1.1483
3311	0.000066	0.000136	0.001657	0.000178	-0.00095	-0.00093	0.000121	0.001505	0.000402	0.000597	1.2396
3613	0.000069	0.000160	0.001910	0.000196	-0.00109	-0.00099	0.000139	0.001755	0.000440	0.000607	1.3309
3914	0.000075	0.000199	0.002293	0.000214	-0.00131	-0.00109	0.000164	0.002173	0.000498	0.000654	1.4693
4217	0.000077	0.000224	0.002566	0.000246	-0.00156	-0.00118	0.000186	0.002459	0.000529	0.000669	1.5768
4519	0.000081	0.000250	0.002831	0.000336	-0.00184	-0.00136	0.000212	0.002791	0.000572	0.000689	1.7084
4619	0.000082	0.000258	0.002953	0.000443	-0.00198	-0.00152	0.000216	0.002942	0.000595	0.000699	1.7778
4696	0.000082	0.000262	0.003099	0.000726	-0.00224	-0.00229	0.000211	0.003243	0.000640	0.000759	1.9876
4628	0.000081	0.000233	0.003280	0.000894	-0.00250	-0.00970	0.000045	0.002934	0.000740	0.000699	2.3688

Curved 4 Panel Positive Moment - Test 1

Load (lbs)	Strain Gauge Measurements (in/in) 1	2	3	4	5	6	7	8	9	10	Deflections (in) d1	d2
0	0.000003	0.000002	0.000004	0.000001	0.000000	0.000002	0.000002	-0.00000	0	0	0	0
2005	-0.00018	0.000018	-0.00018	-0.00001	-0.00001	-0.00000	0.000014	0.000153	0.000001	-0.00009	0.278303	0.201495
4010	-0.00037	0.000024	-0.00037	-0.00004	-0.00002	-0.00001	0.000027	0.000290	-0.00000	-0.00020	0.546623	0.387105
5015	-0.00047	0.000019	-0.00046	-0.00005	-0.00003	-0.00001	0.000035	0.000360	-0.00000	-0.00026	0.681393	0.482135
6019	-0.00057	0.000014	-0.00055	-0.00006	-0.00005	-0.00001	0.000046	0.000433	-0.00001	-0.00032	0.829033	0.586005
7021	-0.00066	0.000008	-0.00064	-0.00008	-0.00006	-0.00001	0.000058	0.000504	-0.00002	-0.00038	0.973033	0.683205
8023	-0.00073	0.000005	-0.00074	-0.00009	-0.00008	-0.00000	0.000077	0.000556	-0.00003	-0.00043	1.124153	0.784985
9027	-0.00079	0.000005	-0.00085	-0.00010	-0.00010	0.000000	0.000118	0.000621	-0.00004	-0.00047	1.312153	0.898795
10029	-0.00093	0.000017	-0.00090	-0.00010	-0.00013	0.000010	0.000184	0.000621	-0.00006	-0.00056	1.509653	1.010925
10531	-0.00096	0.000015	-0.00095	-0.00010	-0.00014	0.000013	0.000223	0.000621	-0.00007	-0.00060	1.602453	1.063675
6101	-0.00099	0.000002	-0.00116	-0.00009	-0.00018	0.000023	0.000325	0.000611	-0.00009	-0.00067	1.807753	1.164375

Curved 4 Panel - Positive Moment Test 1 (Reload)

Load (lbs)	Strain Gauge Measurements (in/in) 1	2	3	4	5	6	7	8	9	10	Deflections (in) d1	d2
0	0.000001	0.000001	-0.00000	0.000001	-0.00000	0.000004	0	0.000002	0.000000	0.000002	0	0
2005	-0.00015	-0.00000	-0.00013	-0.00001	-0.00001	0.000019	0.000020	0.000103	0.000014	-0.00013	0.272329	0.210097
4012	-0.00031	-0.00001	-0.00028	-0.00003	-0.00004	0.00003	0.000044	0.000225	0.000023	-0.00025	0.560629	0.415907
5017	-0.00038	-0.00002	-0.00036	-0.00003	-0.00006	0.000036	0.000057	0.000283	0.000025	-0.00031	0.710169	0.515407
6020	-0.00045	-0.00002	-0.00043	-0.00004	-0.00007	0.000046	0.000074	0.000342	0.000029	-0.00037	0.843309	0.606647
7020	-0.00052	-0.00002	-0.00050	-0.00005	-0.00008	0.000054	0.000088	0.000398	0.000030	-0.00043	0.964259	0.692407
8022	-0.00059	-0.00002	-0.00056	-0.00005	-0.00010	0.000067	0.000106	0.000453	0.000032	-0.00049	1.093669	0.770837
9025	-0.00065	-0.00002	-0.00062	-0.00005	-0.00011	0.000081	0.000124	0.000507	0.000033	-0.00055	1.206669	0.847157
10027	-0.00071	-0.00002	-0.00069	-0.00005	-0.00012	0.000096	0.000144	0.000568	0.000032	-0.00061	1.312669	0.912547
12538	-0.00085	-0.00002	-0.00084	-0.00006	-0.00015	0.000145	0.000195	0.000717	0.000025	-0.00076	1.575569	1.064507
15046	-0.00098	-0.00002	-0.00097	-0.00004	-0.00014	0.000221	0.000249	0.000825	0.000019	-0.00095	1.818469	1.210487
17556	-0.00120	-0.00000	-0.00105	0.000017	-0.00000	0.000355	0.000306	0.000971	0.000036	-0.00136	2.095669	1.433087
20067	-0.00150	0.000024	-0.00111	0.000079	0.000132	0.000463	0.000339	0.001105	0.000323	-0.00164	2.339169	1.658987
20569	-0.00156	0.000033	-0.00112	0.000091	0.000161	0.000480	0.000343	0.001147	0.000545	-0.00166	2.385669	1.705787
21071	-0.00164	0.000041	-0.00113	0.000101	0.000186	0.000494	0.000341	0.001209	0.000970	-0.00165	2.430869	1.750687
20423	0.000579	0.000304	-0.00026	0.000177	0.000276	0.000501	0.000169	0.000830	0.001839	-0.00064	2.697869	2.227387

Curved 4 Panel Positive Moment - Test 2

Load				Strain Gauge Measurments (in/in)							Deflections (in)	
(lbs)	1	2	3	4	5	6	7	8	9	10	d1	d2
0	-0.00000	0.000000	0.000001	0.000001	0.000000	-0.00000	-0.00000	0.000000	0.000000	0.000001	0	0
1125	-0.00009	-0.00002	0.000256	0.000046	0.000017	0.000001	0.000016	0.000113	-0.00001	-0.00005	0.209832	0.195351
2136	-0.00018	-0.00005	0.000461	0.000079	0.000025	-0.00000	0.000026	0.000227	-0.00001	-0.00011	0.338182	0.293591
4145	-0.00035	-0.00007	0.000871	0.000144	0.000041	-0.00002	0.000047	0.000447	-0.00000	-0.00022	0.615392	0.492611
6157	-0.00048	-0.00001	0.001260	0.000205	0.000056	-0.00003	0.000071	0.000627	0.000004	-0.00632	0.896212	0.680701
8163	-0.00061	0.000035	0.001674	0.000281	0.000081	-0.00005	0.000100	0.000764	0.000029	-0.00040	1.212592	0.878741
10177	-0.00086	0.000083	0.002058	0.000356	0.000089	-0.00007	0.000140	0.000853	0.000036	-0.00052	1.544792	1.088491
12302	-0.00102	0.000144	0.002828	0.000544	0.000085	-0.00003	0.000256	0.000855	0.000033	-0.00067	2.034392	1.346091
13812	-0.00111	0.000179	0.003304	0.000676	0.000136	0.000033	0.000330	0.000848	0.000028	-0.00077	2.313792	1.472291
15826	-0.00124	0.000240	0.004164	0.000875	0.000328	0.000224	0.000459	0.000817	0.000032	-0.00088	2.769592	1.630491
17841	-0.00141	0.000298	0.005013	0.000999	0.000618	0.000425	0.000555	0.000812	0.000040	-0.00095	3.213292	1.774191
19851	-0.00158	0.000341	0.005684	0.001063	0.000837	0.00057	0.000618	0.000811	0.000054	-0.00099	3.578192	1.893791
21864	-0.00178	0.000365	0.006237	0.001093	0.000962	0.000657	0.000653	0.000801	0.000068	-0.00104	3.895392	1.989491
22873	-0.00189	0.000371	0.006486	0.001099	0.001001	0.000682	0.000663	0.000797	0.000073	-0.00107	4.035892	2.037691
23377	-0.00194	0.000371	0.006586	0.0011	0.001014	0.000689	0.000666	0.000796	0.000075	-0.00109	4.095292	2.054891
23880	-0.00198	0.000370	0.006676	0.001101	0.001027	0.000699	0.000670	0.000795	0.000078	-0.00111	4.154592	2.072791
24383	-0.00203	0.000365	0.006744	0.001100	0.001038	0.000707	0.000672	0.000792	0.000079	-0.00113	4.210892	2.086591
14014	0.004603	-0.00713	-0.00321	0.000497	0.000928	0.000637	0.000446	-0.00098	-0.00235	-0.00103	4.290392	0.004791

Curved 4 Panel Positive Moment - Test 3 (unbraced)

Load	Deflections (in)	
(lbs)	d1	d2
0	0	0
2014.69	0.118047	0.208280
4029.69	0.39303	0.438080
6039.99	0.55401	0.684670
8046.99	0.71743	0.960790
10063.99	0.89522	1.264550
12077.99	1.0657	1.621650
14093.99	1.20484	2.007950
14596.99	1.24264	2.111750
15098.99	1.30164	2.223250
15467.99	1.35794	2.344250
15969.99	1.38814	2.425450
16474.99	1.41014	2.517050
16975.99	1.42304	2.613550
17478.99	1.44024	2.713250
17982.99	1.46204	2.815150

Curved 4 Panel Positive Moment - Test 4 (unbraced)

Load (lbs)	Deflections (in) d1	d2
0	0	0
260.715	0.240246	0.266392
1265.855	0.333026	0.396972
2270.755	0.422116	0.522032
3275.055	0.494806	0.638192
4281.655	0.579006	0.763152
5287.055	0.681476	0.906122
6292.855	0.791026	1.058292
7298.855	0.908836	1.238692
830[illegible].[illegible]55	1.016856	1.400572
9306.655	1.136356	1.588892
10312.65	1.253256	1.792092
11821.65	1.431256	2.121392
12826.65	1.557956	2.368592
13833.65	1.720756	2.626992
14840.65	1.856356	2.854192
15844.65	1.970156	3.064992
16346.65	2.041156	3.175492
16850.65	2.143356	3.302892
[illegible]1775.65	2.979456	3.455692

Curved 4 Panel Positive Moment - Test 5 (unbraced)

Load (lbs)	Deflections (in) d1	d2
0	0	0
1932.83	0.306895	0.3735291
3940.63	0.445085	0.5886191
5948.93	0.579335	0.8021291
7964.23	0.715815	1.0266191
9980.23	0.641975	1.2885191
11994.23	0.974565	1.5578191
14005.23	1.136845	1.9069191
16015.23	1.209745	2.2864191
18024.23	1.405945	2.6748191
20039.23	1.499545	3.0536191
22056.23	1.568145	3.3910191
24069.23	1.600445	3.6734191
26078.23	1.632445	3.9094191
265[illegible]6.23	1.644245	3.9624191
27092.23	1.655145	4.0164191
27592.23	1.663745	4.0639191

Straight Single Panel Negative Moment - Test 1

Load	Strain Gauge Measurments (in/in)										Deflection
(lbs)	1	2	3	4	5	6	7	8	9	10	(in)
0	0.000000	0.000000	-0.00000	0.000000	-0.00000	0.000001	-0.00000	0.000002	-0.00000	0.000000	0
200	-0.00003	-0.00002	-0.00002	0.000011	0.000037	0.00005	0.000018	-0.00000	-0.00002	-0.00003	0.033724
505	-0.00008	-0.00006	-0.00005	0.000027	0.000092	0.000115	0.000042	-0.00002	-0.00005	-0.00007	0.063418
905	-0.00013	-0.00010	-0.00008	0.000043	0.000147	0.000178	0.000065	-0.00004	-0.00008	-0.00012	0.093081
1107	-0.00018	-0.00013	-0.00011	9.000063	0.000206	0.000240	0.000090	-0.00006	-0.00011	-0.00017	0.120117
1408	-0.00024	-0.00017	-0.00015	0.000080	0.000267	0.000298	0.000114	-0.00008	-0.00015	-0.00024	0.152177
1711	-0.00030	-0.00021	-0.0002	0.000097	0.000334	0.000359	0.000135	-0.00012	-0.00019	-0.00031	0.184877
2013	-0.00038	-0.00024	-0.00026	0.000106	0.000401	0.000431	0.000149	-0.00019	-0.00024	-0.00037	0.220967
2315	-0.00049	-0.00027	-0.00032	0.000119	0.000467	0.000504	0.000160	-0.00026	-0.00030	-0.00040	0.263077
2617	-0.00063	-0.00031	-0.00039	0.000134	0.000523	0.000575	0.000166	-0.00033	-0.00035	-0.00041	0.308477
2920	-0.00083	-0.00035	-0.00049	0.000148	0.000579	0.000652	0.000170	-0.00042	-0.00040	-0.00042	0.356207
3221	-0.00108	-0.00038	-0.00063	0.000152	0.000641	0.000717	0.000175	-0.00049	-0.00053	-0.00047	0.416247
3525	-0.00154	-0.00043	-0.00099	0.000067	0.000698	0.000738	0.000184	-0.00046	-0.00055	-0.00047	0.528507
3827	-0.00189	-0.00048	-0.00118	0.000011	0.000746	0.000810	0.000161	-0.00050	-0.00078	-0.00036	0.615937
3885	-0.00359	-0.00033	-0.00101	-0.00014	0.000612	0.000972	-0.00004	-0.00085	-0.00016	0.000069	0.811117
3986	-0.00318	-0.00022	-0.00094	-0.00019	0.000577	0.001167	-0.00033	-0.00137	0.000685	0.000399	0.936697
4036	-0.00294	-0.00016	-0.00090	-0.00023	0.000545	0.001286	-0.00058	-0.00168	0.000849	0.000600	1.069187
3983	-0.00277	-0.00011	-0.00087	-0.00026	0.000507	0.001333	-0.00067	-0.00170	0.000784	0.000712	1.228687

Curved Single Panel Negative Moment - Test 1

Load (lbs)	Strain Gauge Measurments (in/in) 1	2	3	4	5	6	7	8	9	10	Deflections (in)
0	-0.00000	0.000001	-0.00000	-0.00005	0.000011	-0.00000	-0.00000	-0.00003	0.000001	0.000002	0.0000
305	-0.00002	-0.00000	0.000027	0.000123	0.000051	0.000116	0.000016	-0.00007	-0.00000	-0.00000	0.0775
608	0.000035	-0.00001	0.000048	0.000194	0.000102	0.00022	0.000038	-0.00016	-0.00000	-0.00001	0.1584
908	-0.00005	-0.00001	0.000079	0.000141	0.000179	0.000329	0.000055	-0.00032	0.000001	-0.00002	0.3061
1209	-0.00006	-0.00001	0.000105	0.000130	0.000245	0.000439	0.000079	-0.00049	0.000006	-0.00003	0.4999
1509	-0.00006	-0.00000	0.000129	0.000091	0.000312	0.000547	0.000103	-0.00058	0.000018	-0.00003	0.6329
1811	-0.00007	-0.00000	0.000165	0.000035	0.000368	0.000661	0.000128	-0.00063	0.000033	-0.00003	0.8057
2111	-0.00008	-0.00000	0.000211	-0.00002	0.000414	0.000778	0.000159	-0.00064	0.000058	-0.00003	0.9679
2710	-0.00010	0.000012	0.000279	-0.00022	0.000490	0.001001	0.000235	-0.00058	0.000123	-0.00002	1.3892
2660	-0.00010	0.000018	0.000291	-0.00027	0.000494	0.001038	0.000260	-0.00061	0.000135	-0.00002	1.5485
2782	-0.00010	0.000025	0.000296	-0.00032	0.000506	0.001061	0.000266	-0.00058	0.000143	-0.00001	1.6053
2881	-0.00010	0.000032	0.000299	-0.00037	0.000528	0.001099	0.000264	-0.00055	0.000152	-0.00000	1.6917
2981	-0.00009	0.000039	0.000298	-0.00042	0.000555	0.001138	0.000260	-0.00054	0.000160	-0.00000	1.7900
1540	-0.00007	-0.00000	0.000178	-0.00018	-0.00002	0.000444	0.000161	0.000339	0.000119	0.000035	2.6688

Curved Single Panel Negative Moment - Test 2

Load (lbs)	Strain Gauge Measurments (in/in) 1	2	3	4	5	6	7	8	9	10	Deflection (in)
0	0.000000	-0.00000	-0.00000	-0.00000	0.000000	-0.00002	-0.00000	0.000000	-0.00000	-0.00000	0.0000
225	0.000000	-0.00000	0.000021	-0.00000	0.000065	0.000043	-0.00000	-0.00000	0.000011	0.000014	0.0368
526	0.000001	0.000004	0.000052	-0.00001	0.000137	0.000121	-0.00001	-0.00001	0.000031	0.000035	0.0840
726	-0.00000	0.000006	0.000086	-0.00002	0.000183	0.000178	-0.00001	-0.00003	0.000047	0.000048	0.1193
1026	-0.00000	0.000010	0.000127	-0.00003	0.000252	0.000253	-0.00001	-0.00004	0.000070	0.000074	0.1757
1226	-0.00000	0.000012	0.000149	-0.00003	0.000302	0.000297	-0.00002	-0.00005	0.000085	0.000093	0.2385
1528	0.000001	0.000020	0.000190	-0.00004	0.000377	0.000371	-0.00002	-0.00007	0.000116	0.000128	0.2994
1730	0.000004	0.000027	0.000213	-0.00005	0.000428	0.000423	-0.00003	-0.00008	0.000136	0.000150	0.3395
2032	0.000007	0.000036	0.000250	-0.00006	0.000503	0.000505	-0.00003	-0.00010	0.000170	0.000187	0.4045
2333	0.000014	0.000049	0.000297	-0.00007	0.000581	0.000592	-0.00003	-0.00012	0.000212	0.000233	0.4730
2633	0.000020	0.000067	0.000361	-0.00009	0.000658	0.000686	-0.00004	-0.00013	0.000262	0.000285	0.5443
2933	0.000025	0.000081	0.000457	-0.00009	0.000753	0.000779	-0.00002	-0.00012	0.000310	0.000335	0.6126
3235	0.000032	0.000100	0.000568	0.00009	0.000857	0.000879	-0.00000	-0.00009	0.000370	0.000392	0.6879
3536	0.000040	0.000128	0.000704	-0.00010	0.000969	0.000994	0.000016	-0.00003	0.000446	0.000459	0.7787
3836	0.000055	0.000183	0.000879	-0.00016	0.001088	0.001136	0.000040	0.000054	0.000532	0.000525	0.8933
3937	0.000065	0.000222	0.000970	-0.00021	0.001130	0.001199	0.000054	0.000096	0.000573	0.000561	0.9464
4001	0.000087	0.000398	0.001294	-0.00059	0.001160	0.001347	0.000155	0.000253	0.000178	0.000207	1.0997
2038	0.000069	0.900400	0.001589	-0.00059	0.003401	0.001907	0.000880	0.00049	-0.00446	-0.00181	4.4995

Curved 4 Panel Negative Moment - Test 1

Load	Strain Gauge Measurements (in/in)										Deflections (in)	
(lbs)	1	2	3	4	5	6	7	8	9	10	d1	d2
0	-0.00000	0.000001	0.000007	0	-0.00000	0.000002	0.000000	-0.00000	0	0.000001	0	0
2009	0.000112	-0.00001	-0.00016	0.000011	0.000006	-0.00002	-0.00003	0.000118	-0.00001	-0.00004	0.094839	0.089784
4022	0.000217	-0.00003	-0.00035	0.000023	0.000012	-0.00004	-0.00005	0.000248	-0.00002	-0.00007	0.177489	0.178194
6038	0.000362	-0.00004	-0.00052	0.000040	0.000026	-0.00007	-0.00008	0.000359	-0.00003	-0.00011	0.271789	0.277824
8051	0.000516	-0.00006	0.000701	0.000061	0.000046	-0.00009	-0.00012	0.000480	-0.00005	-0.00017	0.361199	0.384534
10071	0.000658	-0.00005	-0.00092	0.000082	0.000063	-0.00012	-0.00014	0.000585	-0.00008	-0.00022	0.447999	0.476494
12080	0.000787	-0.00001	-0.00119	0.000101	0.000076	-0.00014	-0.00016	0.000688	-0.00013	-0.00027	0.536509	0.565894
14094	0.000928	0.000010	-0.00154	0.000134	0.000096	-0.00016	-0.00019	0.000826	-0.00016	-0.00036	0.634069	0.666714
15098	0.001015	0.000015	-0.00188	0.000161	0.000107	-0.00018	-0.00021	0.000920	-0.00013	-0.00037	0.692889	0.727894
16108	0.001115	0.000019	-0.00248	0.000198	0.000124	-0.00019	-0.00023	0.001022	-0.00009	-0.00036	0.759289	0.797114
16611	0.001177	0.000022	-0.00294	0.000224	0.000135	-0.00021	-0.00025	0.00109	-0.00007	-0.00035	0.803109	0.843704
16097	0.001306	0.000047	-0.00469	-0.00082	0.000303	-0.00031	-0.00057	0.000968	0.000163	-0.00003	1.145099	1.485144

Curved 4 Panel Negative Moment - Test 2

Load	Deflections (in)	
(lbs)	d1	d2
0	0	0
2507.13	0.104626	0.099506
4511.63	0.181736	0.167196
6521.43	0.258026	0.234296
8534.33	0.337916	0.303696
10544.33	0.421856	0.380526
12558.33	0.517886	0.468596
14574.33	0.642306	0.575836
15580.33	0.717986	0.641776
16085.33	0.759976	0.681436
16598.33	0.829666	0.734656
17092.33	0.923746	0.809536
16518.33	1.096556	0.902376

Curved 4 Panel Negative Moment - Test 3

Load	Deflections (in)	
(lbs)	d1	d2
0	0	0
2514.06	0.119568	0.125054
4527.16	0.200958	0.211944
6537.56	0.286208	0.296864
8554.66	0.369958	0.385374
10574.16	0.465368	0.482914
12592.16	0.564878	0.605604
14611.16	0.720518	0.779964
15113.16	0.792558	0.857094
15617.16	0.895308	0.953034
15876.16	1.026778	1.066664

Full Arch - Test 2

Loads (lbs)			Strain Gauge Measurements (in/in)									Deflections (in)		
Load Beam	P1	P2	1	2	3	4	5	6	7	8	9	d1	d2	d3
475	0.0	0.0	0.000008	-0.00000	-0.00000	-0.00000	-0.00000	0.000002	0.000009	0.000002	0.000001	0.0002	-0.0009	-0.0011
475	147.0	157.2	-0.00008	-0.00002	0.000055	0.000022	-0.00016	0.000060	0.000032	0.000002	0.000010	0.1615	0.4693	0.1898
475	310.3	290.6	-0.00020	-0.00004	0.000122	0.000051	-0.00035	0.000127	0.000053	0.000001	0.000019	0.3475	1.0225	0.4123
475	463.3	438.9	-0.00031	-0.00006	0.000189	0.000080	-0.00054	0.000198	0.000073	0.000001	0.000029	0.5258	1.6203	0.6605
475	603.9	600.8	-0.00042	-0.00008	0.000266	0.000115	-0.00080	0.000277	0.000097	0.000001	0.000041	0.7307	2.3135	0.9290
475	770.6	492.3	-0.00057	-0.00010	0.000332	0.00014	-0.00100	0.000346	0.000124	0.000002	0.000050	0.9573	3.1248	1.2107
475	604.2	278.8	-0.00047	-0.00009	0.000344	0.000138	-0.00052	0.000351	0.000121	0.000000	0.000045	1.0300	3.9376	1.2016
475	684.8	307.2	-0.00065	-0.00012	0.000529	0.000213	0.000070	0.000545	0.000178	0.000002	0.000069	1.7545	6.5702	1.8349
475	691.8	381.5	-0.00086	-0.00016	0.000789	0.000323	0.000414	0.000802	0.000265	0.000002	0.000099	2.3637	10.6780	2.5889
475	678.1	458.9	-0.00103	-0.00019	0.001021	0.000443	0.000862	0.001031	0.000353	0.000000	0.000125	2.8357	14.8540	3.3214
475	652.2	476.8	-0.00113	-0.00022	0.001219	0.000532	0.000954	0.001236	0.000353	0.000002	0.000143	3.1576	19.0390	3.9799
475	620.7	462.6	-0.00116	-0.00023	0.001301	0.000557	0.000980	0.001327	0.000342	0.000001	0.000148	3.2835	21.1040	4.2949
475	261.4	195.6	-0.00052	-0.00013	0.001025	0.000410	0.000971	0.001186	-0.00012	0.000001	0.000162	0.1610	21.9920	10.1100
475	309.3	210.5	-0.00062	-0.00014	0.001056	0.000426	0.000994	0.001243	-0.00009	0.000002	0.000174	-0.0301	23.0290	10.0520

Full Arch - Test 3

Loads (lbs)			Strain Gauge Measurements (in/in)									Deflections (in)		
Load Beam	P1	P2	1	2	3	4	5	6	7	8	9	d1	d2	d3
475	0.0	0	0	0	0	0	0	0	0	0	0	0.0000	0.0000	0.0000
475	629.4	458.19	0.000250	-0.00084	-0.00059	-0.00054	-0.00055	-0.00050	0.000265	0.000025	0.024671	2.2348	2.2463	0.9656
475	783.1	610.59	0.000332	-0.00001	-0.00077	-0.00069	-0.00071	-0.00066	0.000351	0.000033	0.032322	3.0071	3.0425	1.2766
475	954.2	742.37	0.000427	-0.00001	-0.00094	-0.00082	-0.00088	-0.00085	0.000447	0.000046	0.041349	3.9576	4.0028	1.6301
475	982.3	408.18	0.000412	-0.00001	-0.00098	-0.00071	0.000989	0.000163	0.000447	0.000041	0.043285	4.4531	4.7836	1.7143
475	601.9	459.88	0.000563	-0.00001	0.000094	-0.01249	0.001951	0.000590	0.000582	0.000058	0.055722	7.5502	7.5584	2.1404
475	613.3	476.78	0.000627	-0.00001	0.000241	-0.01265	0.002128	0.000663	0.000641	0.000068	0.061324	8.6187	8.6009	2.3208
475	614.0	484.21	0.000686	-0.00001	0.000360	-0.01270	0.001991	0.000710	0.000697	0.000077	0.066385	9.6999	9.6558	2.4977
475	585.8	533.54	0.000910	-0.00002	0.000602	-0.01267	0.001946	0.000888	0.000912	0.000131	0.083967	14.0520	13.8560	3.2100
475	587.8	509.22	0.001108	-0.00004	0.000700	-0.01260	0.001798	0.001003	0.001109	0.000218	0.10017	18.3140	18.0410	3.7956
475	321.1	294.99	0.000760	-0.00011	0.000764	-0.01249	0.000821	0.000969	0.000634	0.000252	0.015631	22.4270	22.2910	10.7270

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